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Treatment of Combined Sewer Overflows by High Gradient Magnetic Separation

Sala Magnetics, Inc, Cambridge, Mass

Prepared for

Municipal Environmental Research Lab, Cincinnati, Ohio Wastewater Research Div

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Seeded water treatment by high gradient magnetic separation techniques was carried out on combined storm overflows and raw sewage influents. Both bench-type and continuous pilot plant tests were performed to evaluate the effectiveness of the process in purifying waste waters. Critical parameters were varied to determine optimal removal efficiencies, sensitivities and relative importances of these variables. Attempts were also made to compare the effectiveness and economic feasibility of high gradient magnetic separation treatment with present methods of waste water treatment. Finally, recommendations for the next phase of study have been presented.

The results of the present study show this process to be a highly effective method of reducing most forms of pollutants present in CSO and raw sewage to low levels of contamination. Capital cost estimates for high gradient magnetic separation systems also compare favorably with traditional secondary plants. Several additional benefits are realized such as extremely high processing rates, small land requirement, and lower chlorine demand (ecological benefits). Work on this project was begun in June 1975 and was completed July 1976.

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TREATMENT OF COMBINED SEWER OVERFLOWS BY HIGH GRADIENT MAGNETIC SEPARATION

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the hazardous water pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that reasearch; a most vital communications link between the researcher and the user community.

Many of our cities are faced with pollution problems associated with combined sewer overflows. Contamination of surface waters with sewage occurs following heavy precipitation or snow melts. Conventional treatment has failed to reduce, significantly, pollution caused by these surges of contaminated water. High gradient magnetic separation offers an efficient means of removing pollutants from combined sewer overflow.

Results of earlier studies show that high gradient magnetic separation removes more than ninety percent of suspended solids from water. These include algae, bacteria and viruses as well as non-living biocolloids. The process also removes significant quantities of dissolved BOD, COD, and heavy metals. This report describes bench and pilot level studies of high gradient magnetic separation treatment of combined sewer overflow to the Charles River at Cambridge, Massachusetts.

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Director
Municipal Environmental
Research Laboratory

ABSTRACT

Seeded water treatment by high gradient magnetic separation techniques was carried out on combined storm overflows and raw sewage influents. Both bench-type and continuous pilot plant tests were performed to evaluate the effectiveness of the process in purifying waste waters. Critical parameters were varied to determine optimal removal efficiencies, sensitivities and relative importances of these variables. Attempts were also made to compare the effectiveness and economic feasibility of high gradient magnetic separation treatment with present methods of waste water treatment. Finally, recommendations for the next phases of study have been presented.

The results of the present study show this process to be a highly effective method of reducing most forms of pollutants present in CSO and raw sewage to low levels of contamination. Capital cost estimates for high gradient magnetic separation systems also compare favorably with traditional secondary plants. Several additional benefits are realized such as extremely high processing rates, small land requirements, and lower chlorine demand (ecological benefits).

This report was submitted in fulfillment of Contract No. 68-03-2218 by Sala Magnetics, Inc. under the sponsorship of the U. S. Environmental Protection Agency. This report covers the period of June, 1975 to July, 1976.

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This project was conducted under the supervision of John A. Oberteuffer, Chief Investigator and Bo Arvidson, Process Development Director. All experimental design and testing was carried out by Project Engineers David Allen and Richard Sargent with the help of Susan Winkelman, Laboratory Technician. The report was written by David Allen, and Richard Sargent, with assistance from Ralph Mitchell.

SECTION I

CONCLUSIONS

- Single-step processing of combined storm overflows or of raw sewage with high gradient magnetic separation results in the production of effluents at high flow rates which significantly surpass other secondary process effluents in purity.

- Effluent quality is excellent. The percentage removals of pollutants (average from all testing performed) are given below:

Pollutant	% Removal From: CSO	% Removal From: Sewage
Suspended Solids	95	91
Turbidity	93	88
Apparent Color	87	82
Fecal Coliform	> 99	> 99
BOD_5 (Total)	> 92	--
COD	75	67

- Testing has shown that optimization of parameters (through jar tests and solids loading determinations) can yield even higher removal efficiencies. A summary of the percent removals achieved on a heavily loaded sample of CSO under estimated optimum conditions is given below:

Pollutant	Optimized Run on CSO (% Removals)
Suspended Solids	98.7
Turbidity	96
Apparent Color	93
Fecal Coliform	99.85
BOD_5 (Total)	> 92

- Alum concentration and pH were found to be the most sensitive parameters in the process. Their interactions with each other and with other components in the influent stream were of major importance in the production of good coagulation, essential to this process.

- Polyelectrolyte and magnetic seed concentrations were critical to separation efficiency only when approaching the low ends of their effective concentration ranges. Likewise, magnetic field strength was not critical above a certain minimum level defined by the solids present, seed and flocculants concentrations and flow rate used.

- A detention time of 3 minutes for the entire flocculation-seeding process plus magnetic separation was adequate for all CSO and raw sewage treated. As no large settling tanks are necessary, the turnover time and space requirements for high gradient magnetic separation are much less than for other secondary treatments.

- Flow velocity through the matrix can be varied over fairly wide ranges without substantial changes in effluent quality. Compensation for greatly increased flow velocities can be achieved by increased concentrations of polyelectrolyte and magnetite and higher magnetic fields.

- Surge flows can be handled in the above manner and by putting additional separators into service. Residence times of as little as three minutes are necessary for adequate flocculation and seeding.

- Matrix loadings of about 0.5 gram of solids/gram of matrix fiber can be achieved without significantly affecting effluent quality. Filtration duty cycles exceeding 90% are readily attainable.

- High gradient magnetic separation provides much greater flexibility in adjustment to large variations in flow rate and influent character than conventional systems. High gradient magnetic separation is well suited to automatic operation and produces an effluent that approaches the quality of effluents produced by tertiary treatment systems.

- Estimated capital cost for an integrated wet and dry weather facility is approximately $107,000/mgd and operation and maintenance costs are $0.137/1000 gal. The high gradient magnetic separation capital costs for an integrated facility are approximately 40% lower than comparative physical-chemical treatment. Estimated operation and maintenance costs are approximately 20% lower than physical-chemical treatment processing.

SECTION II

RECOMMENDATIONS

SUMMARY

- On-site operation of pilot plant at existing storm overflow treatment facility.
- Design and construction of demonstration scale integrated dry and wet weather treatment facility (0.5-2.0 mgd).
- Long term operation (6 - 12 month) of demonstration scale system to evaluate system performance.
- Design and construction of full-scale integrated dry and wet weather treatment facility.

DETAILED RECOMMENDATIONS

Phase I - Continued Testing on Existing Pilot Plant

A. Using one storm batch collected from Cottage Farm Station (or in the event of a dry spell, dry weather flow from a sewage treatment plant), the following should be determined:

1. Maximum permissible matrix loadings over a range of at least 3 different magnetite seed to solids ratios.
2. Maximum matrix loading as a function of different matrix construction designs.
3. Upper limit of flow velocity through matrix.
4. Residence time required after each flocculant addition.
5. Effect of simultaneous flocculant additions as well as different addition sequences.

Phase II - On-site Pilot Plant Evaluation

A. Tests at Cottage Farm Station and/or other locality (such as Waterbury, CT).

1. Run the pilot plant for the duration of a storm flow.

2. Finish any testing not completed in Phase I.

3. Determine the effect of different backflushing techniques on effluent quality.

4. Determine minimum backflush volume required for satisfactory matrix flush.

5. Evaluate long term cleaning and replacement requirement for matrix.

6. Evaluate characteristics of sludge obtained during preceding testing.

7. Run system for the duration of one storm with as few changes as necessary in operation to evaluate long-term operation. Particular attention should be directed to the "first flush" of storm flow.

B. Storm flow profile testing (at Cottage Farm Station and/or other locality).

1. Run pilot plant over the duration of 2 storms profiling pilot plant flowrate to storm flow. As flow increases, an additional magnetic separator will be brought on-stream to increase capacity.

C. Pre-engineering and budgetary estimate for demonstration scale integrated wet and dry weather treatment facility.

Phase III - Additional Testing, Demonstration Scale Treatment Facility Engineering

A. Testing at Cottage Farm or other locality.

1. Investigate the use of treated water for backflushing.

2. Additional testing suggested from Phases I and II.

B. Testing at an EPA pilot plant location in conjunction with EPA personnel.

C. Revise (if necessary) pre-engineering and budgetary estimate for a demonstration scale integrated wet and dry weather treatment plant.

Phase IV - Demonstration Scale Integrated Wet & Dry Weather Treatment Facility

A. Construct demonstration treatment plant.

B. Design and conduct test program to evaluate system performance over (6-12 month) period.

Phase V - Construct Full-Scale Integrated Wet & Dry Weather Treatment Facility

The testing should include but not be limited to the studies described above. It is expected that Phases I and II will show the need for additional study of some parameters. The execution of the present study (#68-03-2218) has shown that the suspended solids removals were also representative of the BOD_5, COD and bacteria removal results obtained. Thus it is suggested that for the bulk of the testing in this recommended program only suspended solids and turbidity tests be regularly performed. Other analyses such as BOD_5, COD, heavy metals, coliform, phosphate, etc.. should be performed for selected samples only.

SECTION III

SUMMARY

High gradient magnetic separation has been tested for treatment of combined storm overflows. The data show that this process is highly effective for the removal of suspended solids, turbidity, apparent color, BOD5 and fecal coliform bacteria. These removals can be achieved at high process flow velocities in a single pass through a high gradient magnetic separator. Results show this technique to substantially surpass present methods of secondary treatment in effluent quality. Furthermore, estimated cost comparisons for similar capacity systems show that high gradient magnetic separation is economically competitive. Thus, it appears from the present study that the high gradient magnetic separation process can purify CSO more effectively than can any other secondary-type treatment.

OPTIMAL PERFORMANCE

The table below shows data from a continuous pilot test on CSO in which estimated optimal conditions were set and unchanged over a period of approximately one hour of running time. Ten grab samples were taken (one each from ten consecutive cycles) during this interval for analysis.

TABLE III - 1

	SUSPENDED SOLIDS (mg/l)	APPARENT COLOR (PCU)	TURBIDIITY (FTU)	FECAL COLIFORM (cells/100 ml)	TOTAL BOD_5 (mg/l)	COD (mg/l)
FEED						
Average	460	650	230	$3.6x10^{7}$	>79	410
(# tests)	(3)	(3)	(3)	(4)	(2)	(2)
Range	400-520	600-800	200-250	$2.0\text{-}5.0x10^{7}$	>75-83	395-425
TREATED						
Average	6.0	47	8	$5.3x10^{4}$	6.0	106
(# tests)	(9)	(10)	(10)	(6)	(4)	(5)
Range	4.1-9.1	41-53	8-11	$1.5\text{-}13x10^{4}$	5.2-7.0	92.7-138
AVERAGE % REMOVAL	98.7%	92.8%	96.3%	99.85%	>92%	74%

SUMMARIZED AVERAGE DATA

The tables shown below give averages for all tests performed throughout the project (tables in Appendix A break down data into separate CSO and raw sewage samples). These data necessarily include many non-optimized runs, as the objective of these tests was to vary certain parameters over wide ranges to determine best running conditions and relative importances of these variables. Thus the following averages are underestimates of the achievable effectiveness of magnetic separation.

Solids Removal

The results of the tests described herein clearly show that high gradient magnetic separation is a highly effective solids removal means for combined sewer overflow and raw sewage. Average percent removals obtained from all bench and pilot plant tests combined are listed below:

TABLE III-2

	CSO % REMOVAL	SEWAGE % REMOVAL
Suspended Solids (Nonfiltrable Residue)	95	91
Settleable Solids	99^+	99^+
Apparent Color	87	82
Turbidity	93	88

Biological Material Removal

The efficiency of removal of biological organisms such as bacteria, algae and viruses is very high. Listed below are combined bench and pilot plant results achieved for these materials:

TABLE III - 3

	AVERAGE % REMOVAL
Total Coliform Bacteria on EMB agar at 37°C	99.3
Fecal Coliform on EMB agar at 37°C	99.2
Algae(1)	99.9
Virus, Bacteriophage T_7(2)	100
Virus, Polio*	99-100

The total biochemical oxygen demand of the feed was reduced significantly. An average reduction of greater than 92% was achieved.

* Data from Bitton (See Table IV-4) and Metcalf (See Table IV-5)

Removal of Chemical Species

The seeded high gradient magnetic separation treatment reduced the total chemical oxygen demand of CSO and sewage samples by an average of 74%. Removal of heavy metal species was similarly excellent. Average reductions observed for various heavy metals are listed below:

TABLE III - 4

METAL	AVERAGE % REDUCTION (Range)
Cd	> 43%
Cr	> 41%
Cu	53%
Pb	(0-67%)
Hg	> 71%
Ni	(0-67%)
Zn	84%

REMOVAL EFFECTIVENESS IN COMPARISON TO CONVENTIONAL TREATMENT

The removal efficiencies of SALA seeded water treatment demonstrated in this study can be compared to those of conventional treatment processes. Average percent removals for high gradient magnetic separation treatment and conventional processes for CSO and raw sewage are compared in Tables III-5 and III-6.

PARAMETER RANGES TESTED

The operational parameters considered in this study were concentrations of seed and flocculants, flow velocity, magnetic field strength, pH, floc train residence time, and matrix loading. Evaluation of the relative importance of each parameter was made by considering effects of parameter change on percent removal of suspended solids, color, turbidity, bacteria, BOD_5 and COD.

Operational parameters were varied over the following ranges:

Applied Magnetic Field:	0.1 to 1.9 kG
Flow Velocity:	60 to 300 m/hr
Alum Concentration:	0 to 200 mg/1
Seed (Magnetite) Concentration:	50 to 5000 mg/1
Polyelectrolyte (Betz 1150) Concentration:	0 to 3.0 mg/1
pH:	4.5 to 7.5
Matrix Loading:	0.01 to 1.0 g solids/g matrix
Floc Chain Residence Time:	1 to 10 min

TABLE III - 5

RELATIVE EFFICIENCIES OF CSO TREATMENT OPERATIONS(3)

TREATMENT PROCESS	% Removal			
	SUSPENDED SOLIDS	BOD_5 (TOTAL)	COD	COLIFORM BACTERIA
High Gradient Magnetic Separation*	92-98	90-98	70-85	99-99.99
Rotating Biological Contactor	70	54	---	---
Contact Stabilization	92	83	---	83
High Rate Trickling Filtration	65	65	---	83
Treatment Lagoon	(-4)-92	27-91	---	72-96
Chemical Clarification	90-98	70-80	---	40-80
Dissolved Air Flotation with Fine Screening	56-77	41-57	41-45	---
Fine Screening	35-40	15	---	10-20
Microstraining(4)	70	50	37	3-99
Sedimentation	60	30	---	25-75
Dual Media Filtration with Polyelectrolyte(5)	36-92	66-79	66-79	---

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* Average percent removal for all Pilot Plant and Bench Tests done on CSO by Sala Magnetics.

TABLE III - 6

RELATIVE EFFICIENCIES OF SEWAGE TREATMENT OPERATION AND PROCESSES *

TREATMENT PROCESS	% Removal		
	SUSPENDED SOLIDS	COD	COLIFORM BACTERIA
High Gradient Magnetic Separation **	88-95	60-75	99-99.9
Chlorination of Raw or Settled Sewage	---	---	90-95
Plain Sedimentation	40-70	20-35	35-75
Chemical Precipitation	70-90	40-70	40-80
Trickling Filtration Preceded and Followed by Plain Sedimentation	50-92	50-80	90-95
Activated Sludge Treatment	55-95	70-80	90-98

---

* G.M. Fair, J.C. Geyer, and D.A. Okun, Water Purification and Water Treatment and Disposal, Vol. 2, John Wiley & Sons, New York, 1968, pp. 21-72.

** Average percent removals for all Pilot Plant and Bench Tests done on raw sewage by Sala Magnetics.

Those variables found to be most sensitive to change for good removal efficiencies in early bench tests were explored in more detail in the later pilot plant runs and bench tests.

RELATIVE IMPORTANCES, SENSITIVITIES AND INTERACTIONS OF PARAMETERS

The two parameters having the most relative importance on removal efficiency are coagulant (alum) concentration and pH. For each sample collected, a slightly different concentration of alum is necessary for optimal flocculation. This is explained both by the differences in pH of the individual samples and by the character and amount of solids loading. Thus alum is a quite sensitive parameter requiring precise dosing for good flocculation.

Required polyelectrolyte concentrations vary much less than alum, and polyelectrolyte can be omitted altogether for low flow rates, as its chief value is in bridging and strengthening already existing alum-solid aggregates. Optimum pH likewise seems to vary not only with the nature of the waste (bacterial polymers present, etc.), but also with the relative amounts of alum and polyelectrolyte being used, since these agents have optimum flocculation pHs of ∿ pH6 and ∿ pH8 respectively. At higher processing rates however, use of polyelectrolyte may be necessary for successful magnetic separation in order to compensate for floc disruption caused by higher hydrodynamic shear forces.

Matrix loading is also an important parameter, as it is directly related to the influent solids loading and the magnetic seed concentration used (which in turn are related to each other). Breakthrough occurs when the magnetic matrix is overloaded with sludge. Thus, the flushing interval (cycle time) must be varied with influent solids load as well as with process flow rate. Flow velocity itself seems to be a relatively insensitive parameter within our test range except when matrix loading or low polyelectrolyte concentrations are involved. Changes in efficiency of separation of only a few percentage points were observed over the velocities tested.

Magnetite concentration, magnetic field strength and floc chain residence time are relatively insensitive parameters above certain minimum values. Magnetite concentrations necessarily depend directly on the solids present in the feed. A ratio of 1:1 produced good separation. Magnetic fields as low as 0.5 kG were sufficient on all feeds tested, but it can be assumed that at higher flow velocities, where shearing effects are more critical, higher fields may be necessary. Mixing times necessary for good flocculation were short (on the order of three minutes). Longer mixing times (up to ten minutes) did not give significantly better separation.

SECTION IV

INTRODUCTION

OVERVIEW OF HIGH GRADIENT MAGNETIC SEPARATION

Magnetic separation techniques have been used since the nineteenth century to remove tramp iron and to concentrate iron ores. A variety of conventional magnetic separation devices are in wide use today. These devices generally separate relatively coarse particles of highly magnetic material containing large amounts of iron from non-magnetic media.

In recent years magnetic devices have been developed which are capable of separating even weakly magnetic materials of micron size at inherently high flow rates. These so-called "high gradient magnetic separators" have been designed to maximize the magnetic forces on fine, paramagnetic materials. They are capable of efficient separation of even weakly magnetic suspended solids or precipitates for which conventional magnetic separation techniques are ineffective. The separations may be carried out economically and at process rates of up to several hundred gpm/ft^2.

For normally non-magnetic colloidal material in polluted water the addition of small quantities of magnetic iron oxide (magnetite) renders these colloids sufficiently magnetic to be removed by high gradient magnetic separators. The machines provide the rapid filtration of many pollutants from water, with a small expenditure of energy. Removal is much more efficient than with sedimentation because the magnetic forces on fine particles may be many times greater than gravitational forces. This technology has a high potential for application to water pollution control.

High gradient magnetic separation is currently used in the kaolin clay industry for the removal of weakly magnetic impurities less than 2 microns in diameter from clay. High gradient magnetic separators treating up to 60 tons per hour of dry clay as a 30 percent slurry are industrial-size units. A Sala pilot plant capable of processing up to 5 tph of kaolin slurry is shown in Figure IV-1. These high gradient magnetic separators are the result of the development of a filamentary ferromagnetic matrix and a large volume high field magnet. This combination of an efficient magnet and high gradient matrix permits the economical production of strong magnetic forces over a large surface area in the active volume of the separator.

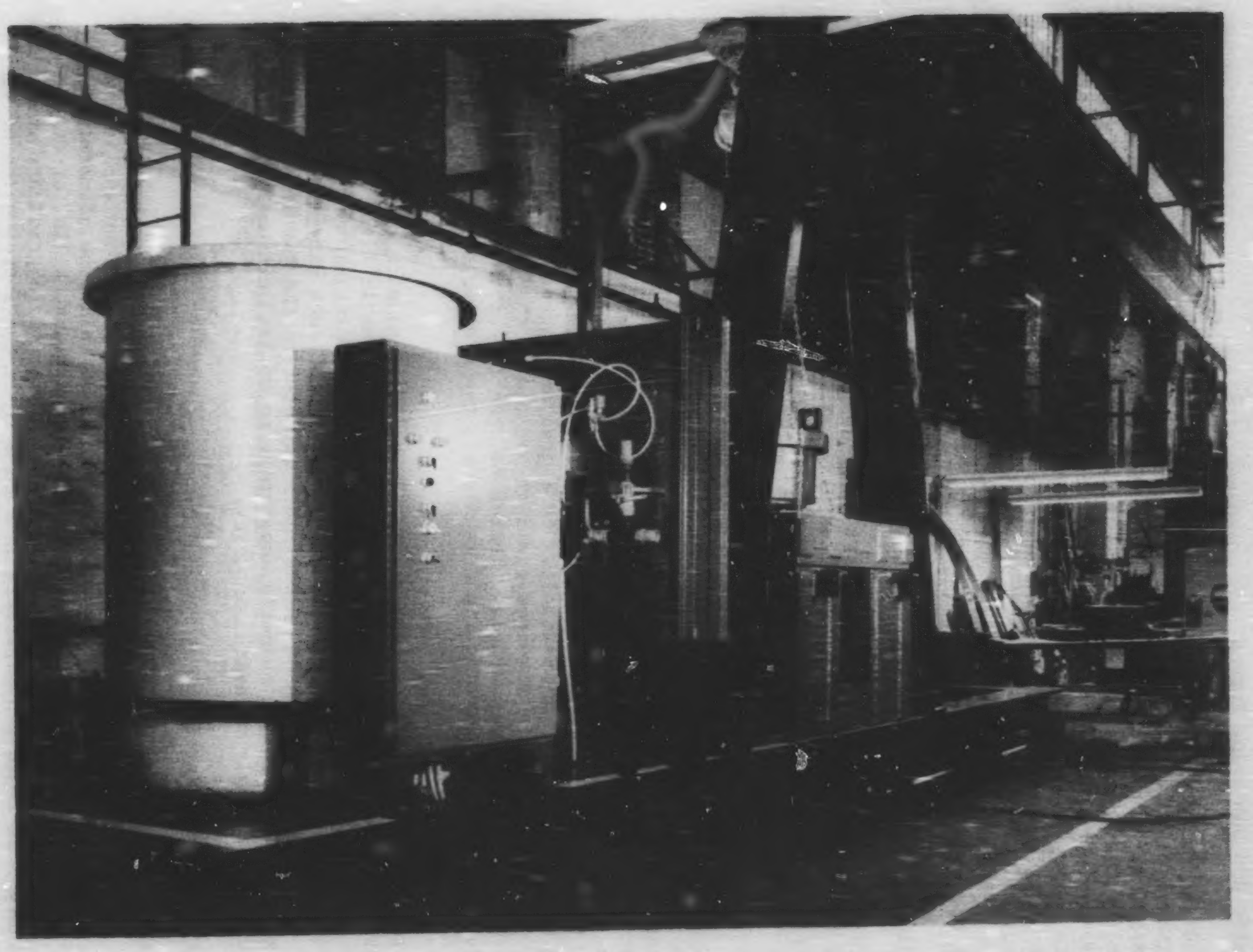


FIGURE IV-1 SALA 5 TPH KAOLIN CLAY PILOT PLANT

PRINCIPLES OF HIGH GRADIENT MAGNETIC FILTRATION

Magnetic and Competing Forces

High gradient magnetic separators, like all magnetic separators, utilize the interaction of magnetic and competing forces on a mixture of magnetic and non-magnetic particles to provide separation based on the magnetic susceptibilities of the particles. The magnetic forces of attraction in a high gradient magnetic separator hold the magnetic particles to the edges of the matrix fibers while the competing hydrodynamic forces carry the fluid and non-magnetic particles through the separator. For small particles the forces of hydrodynamic drag are larger than gravitational forces, and increase with slurry velocity in the separator. The magnetic forces necessary to trap these particles must, therefore, be large.

Maximizing the Magnetic Forces

High gradient magnetic separators effectively maximize the magnetic force on even weakly magnetic particles(6,7). The magnetic force (F_m) on a particles is given by the following expression:

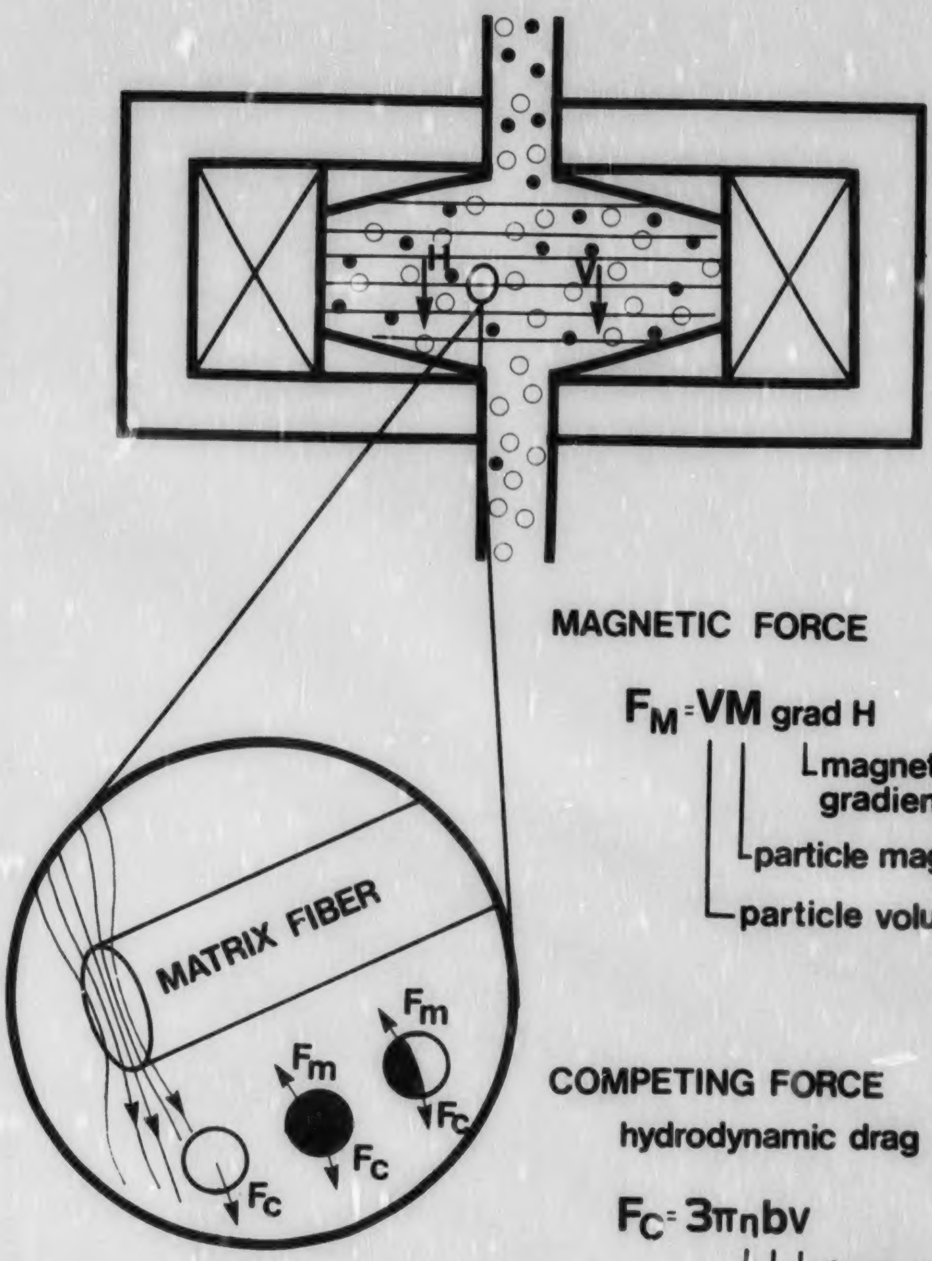
$$F_m = vM \text{ grad } H$$

where v is the volume of the particle, M is its magnetization, and grad H is the magnetic field gradient that acts on the particle. The magnetic field gradient appears in the expression for magnetic force for the following reason. Placed in a magnetic field, all particles develop north and south poles at either end as shown in Figure IV-2. In a uniform field the net force on a particle will be zero since the field exerts an equal and opposite force on either end of the particle. In a gradient magnetic field, however, the force exerted by the stronger field at one end of the particle will produce a net force on the particle. Therefore, the larger the change in field across the particle (magnetic field gradient), the greater the force on the particle.

The magnetization of ferromagnetic fibers like those in the high gradient magnetic separator matrix produces extremely high magnetic field gradients. It turns out that the greatest force is produced on the particles when the diameter of the magnetized wire is approximately the same size as the particle to be trapped. This matching of the fiber diameter to the particle size is utilized in high gradient magnetic separators to produce extremely large forces on even weakly magnetic particles.

The Ferromagnetic Matrix

In order to produce strong magnetic forces over a practical surface area, a filamentary ferromagnetic matrix magnetized by a strong applied field is used(8). The effective trapping volume of this type of matrix is many times larger than that achieved by the use of tacks, balls, or other small ferromagnetic objects which also produce large field gradients when magnetized. As shown schematically in Figure IV-2, the introduction of the



MAGNETIC FORCE

$F_M = VM \text{ grad } H$

magnetic field gradient

particle magnetization

particle volume

COMPETING FORCE

hydrodynamic drag

$F_C = 3\pi\eta b v$

slurry velocity

particle diameter

slurry viscosity

FIGURE IV-2

CUTAWAY VIEW OF HIGH GRADIENT MAGNETIC SEPARATOR

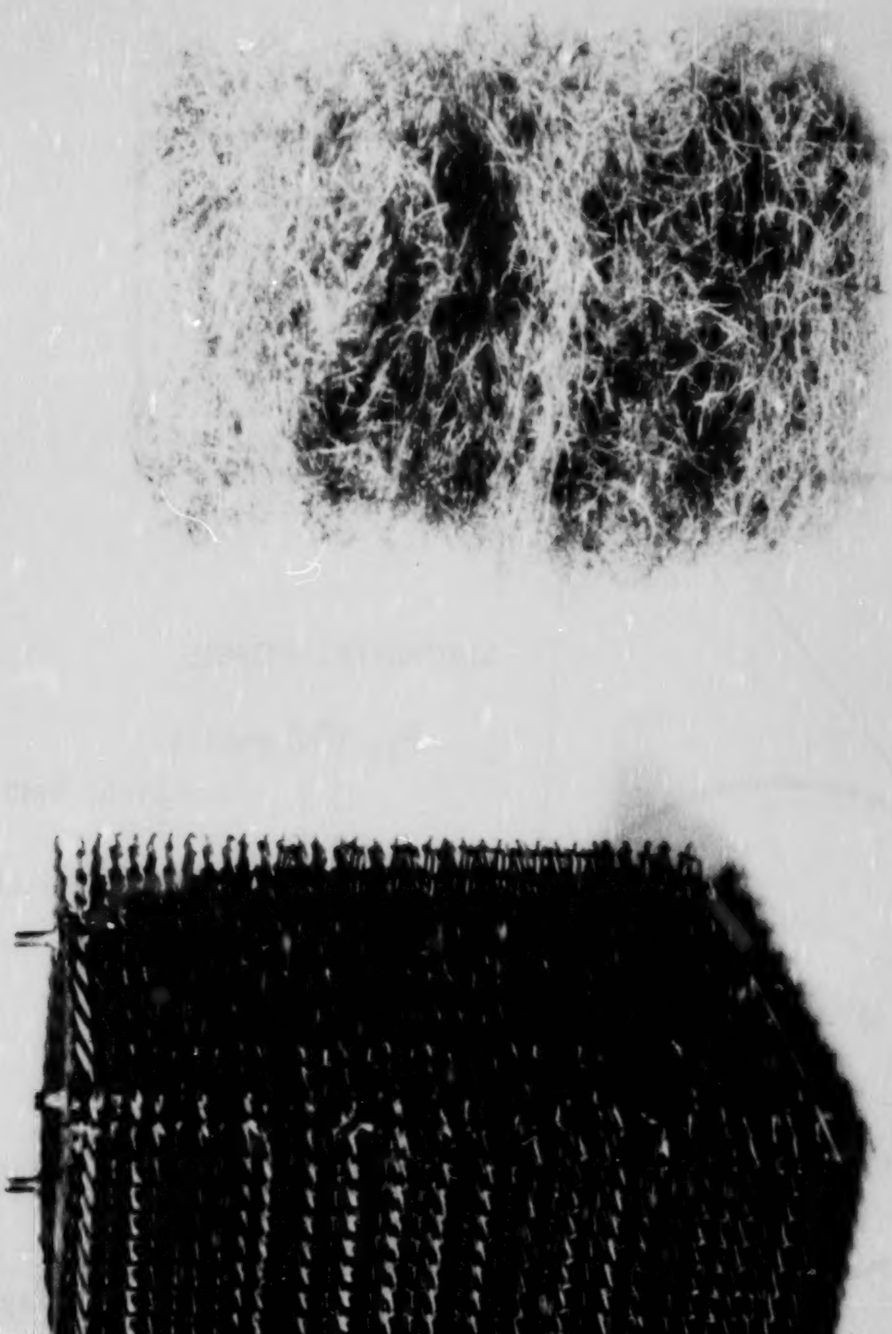


FIGURE IV-3 MATRIX MATERIALS USED IN HIGH GRADIENT MAGNETIC SEPARATORS

ferromagnetic matrix into the uniform magnetic field produced by the electromagnets in the high gradient magnetic separator, produces a multitude of high gradient strong forces within the volume of the separator. A strong applied field is required to magnetize these fibers, and when this field is turned off, the residual magnetization of the fibers is very low. For this reason even strongly magnetic particles are easily washed out when the applied field is reduced to zero. Typical matrix materials are shown in Figure IV-3.

Production of Strong Magnetic Fields

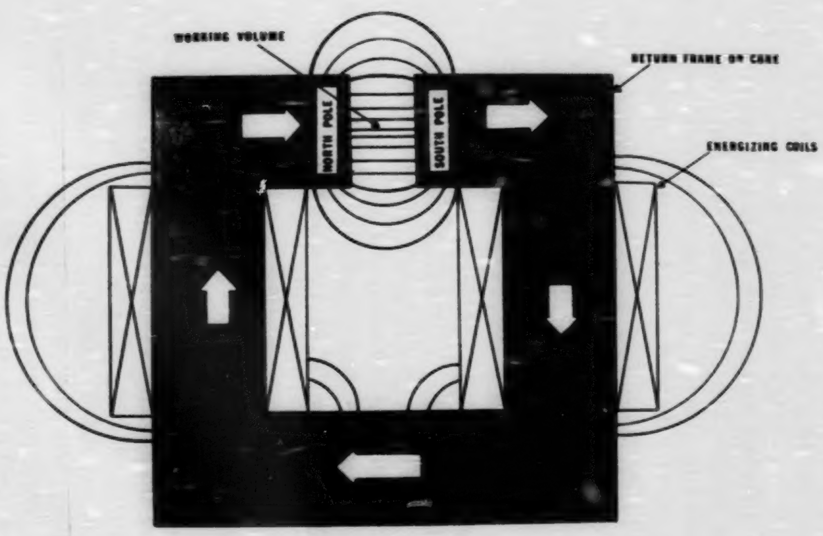
The ferromagnetic matrix is a relatively difficult magnetic structure to magnetize--that is, a large strong applied magnetic field is required to produce high field gradients along the matrix filament edges. The magnetic fields in conventional magnetic separation devices are not sufficient to magnetize the ferromagnetic matrix. Therefore, practical realization of high gradient magnetic separation depends as much on the production of an economical, intense magnetic field as it does on the ferromagnetic matrix.

It is useful to compare the design of prior art magnets with those used in high gradient magnetic separators. Figure IV-4A shows a magnetic circuit commonly used for producing strong magnetic fields in conventional and some competing high intensity magnetic separators. The magnetic field in the working volume is produced by magnetic poles in the iron on either side of the gap. The electromagnetic energizing coils are placed on vertical legs of the magnet circuit in order to magnetize the iron. Much of the field produced by the coils in iron, however, never reaches the working volume but leaks around it through magnetic short circuits. The electromagnetic coils contribute nothing directly to the magnetic field of the working volume since they are placed away from the working volume on the yoke of the magnet.

By contrast, in Figure IV-4B the magnetic circuit of the Sala design is shown superimposed on the prior art circuit. The electromagnetic coil is placed directly around the working volume where it contributes directly to the field within that volume as well as to the magnetization of the iron poles on either side of the working volume. A small iron return path around the Sala coil further increases the efficiency of the circuit. It is clear that considerable savings in iron have been achieved for the same working volume. In addition, the magnetic field produced in the new magnet is considerably more powerful for the same input of electrical energy than in prior art devices.

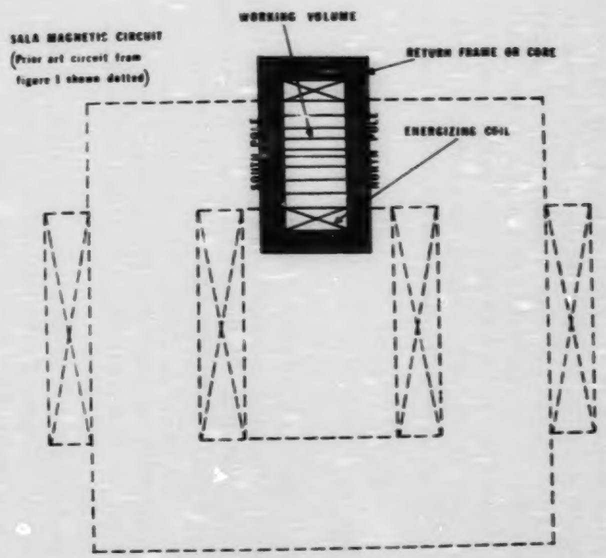
The Operating Variables of the Separator

The efficiency of magnetic particle trapping in a high gradient magnetic separator depends heavily upon the operating variables of the separator as well as the size and magnetic susceptibility of the particles. The operating variables are: the strength of the applied magnetic field; the velocity of the feed passing through the matrix; and the ratio of the feed material weight (percent of solids) to the working volume of the separator. The recovery of the magnetic particles increases with an increasing magnetic


WORKING VOLUME
RETURN FRAME OR CORE
ENERGIZING COILS
NORTH POLE
SOUTH POLE

Prior Art Magnetic Separator

FIGURE IV-4A


SALA MAGNETIC CIRCUIT
(Prior art circuit from
figure I shown dotted)
WORKING VOLUME
RETURN FRAME OR CORE
ENERGIZING COIL
SOUTH POLE
NORTH POLE

Sala Magnetic Separator Compared to Prior Art Magnetic Separator

FIGURE IV-4B

COMPARISON OF PRIOR ART AND SALA HIGH GRADIENT MAGNETIC SEPARATORS field because the magnetic forces are stronger. The recovery of the magnetic particles decreases with increasing feed flow velocity because the competing hydrodynamic drag forces are larger. The recovery of magnetic particles decreases with increased matrix loading since high gradient trapping sites within the matrix volume become filled, leaving fewer available trapping sites. The optimization of the operating variables described here is important since these variables significantly affect the capital and processing costs in the practical use of high gradient magnetic separators.

HIGH GRADIENT MAGNETIC SEPARATORS

In its simplest form, the high gradient magnetic separator consists of a canister packed with a fibrous ferromagnetic material and magnetized by a strong external magnetic field. A schematic cross-section of a static high gradient magnetic separator is shown in Figure IV-5. The magnetic matrix shown at the center is magnetized by the coils (indicated by crosses) which surround the canister. An iron frame increases the efficiency of the electromagnetic coils. The device operates in a sequence of feed and flush modes. A feed slurry containing the particles to be separated is passed through the device with valves 1 and 3 open. The magnetic particles are trapped on the edges of the magnetized fibers while the non-magnetic particles and slurry fluid pass easily through the canister. The matrix offers only a small hydraulic resistance to the feed flow, occupying less than 5% of the canister volume (95% void volume). When the matrix has become loaded with magnetic particles, valves 1 and 3 are closed and the magnetic particles are easily washed from the matrix by reducing the magnetic field to zero and opening valves 2 and 4 to permit backflushing. High gradient magnetic separators of this type, termed "static," "batch," or "cyclic" devices are used to process fluids and minerals containing a low percentage of magnetic impurity. Cyclic devices may be operated automatically and quasi-continuously by use of feed surge tanks. Separators of this design are useful for water treatment.

HIGH GRADIENT MAGNETIC FILTRATION TECHNIQUES IN WATER TREATMENT

The use of high gradient magnetic separation or filtration in water treatment may be accomplished in two ways depending on the nature of the contaminants in the water. For waters contaminated by magnetic suspended solids, such as steel mill waste waters and the corrosion products of boiler waters, high gradient magnetic filtration may be used alone to effectively remove these particles ("direct filtration").

High gradient magnetic separation may also be used to remove non-magnetic contaminants from water. This is accomplished by binding finely divided magnetic seed particles to the non-magnetic contaminants, thus creating a "magnetic handle" ("indirect filtration" or "seeded water treatment").

Binding of the magnetic seed is accomplished in two general ways: adsorption of the contaminant to magnetic seed and chemical coagulation. Particles ranging in size from soluble through settleable (>0.001 μ) may be removed with this process.

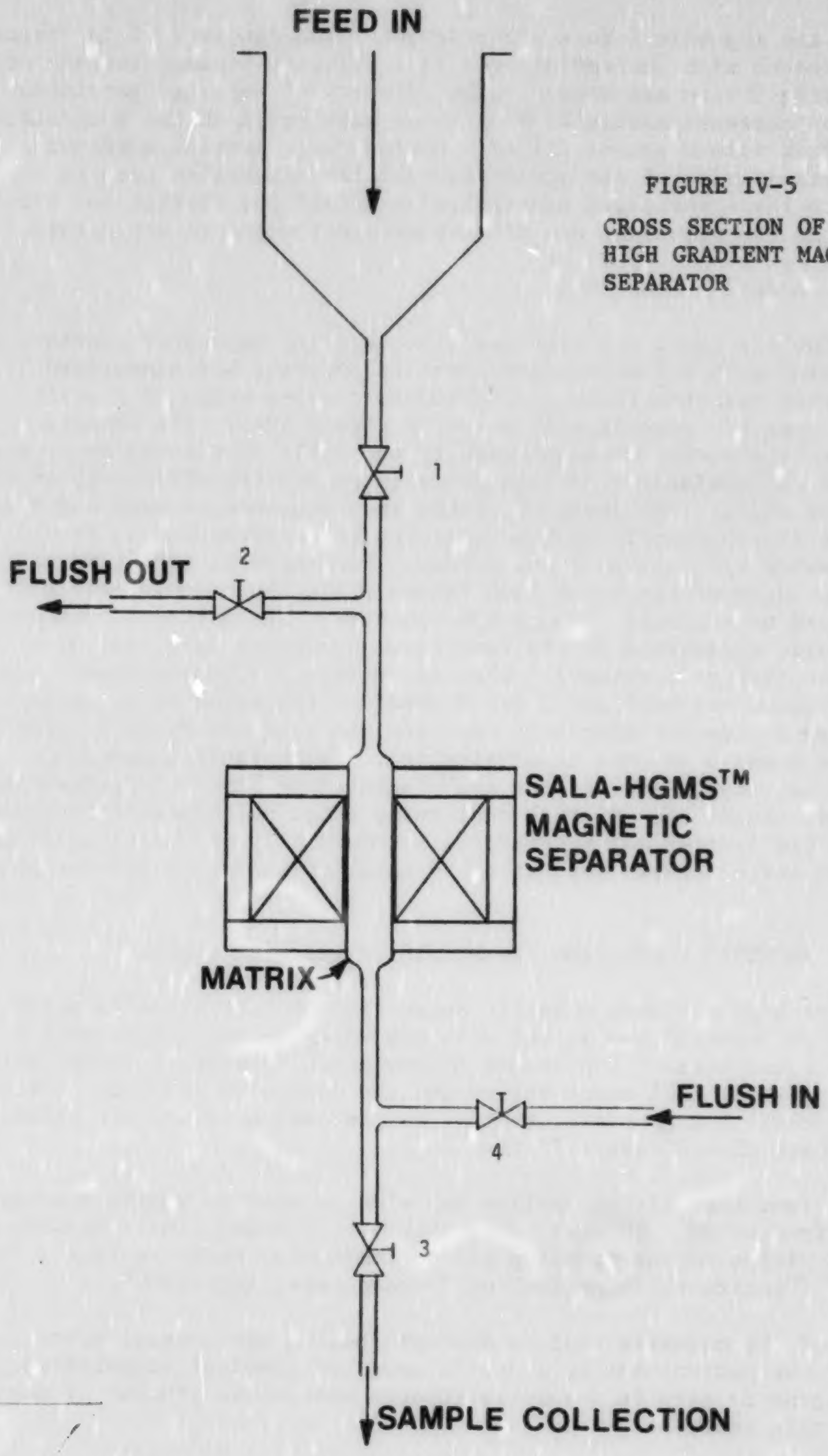

FEED IN
1
2
FLUSH OUT
SALA-HGMS™
MAGNETIC
SEPARATOR
MATRIX
FLUSH IN
4
3
SAMPLE COLLECTION

FIGURE IV-5

CROSS SECTION OF STATIC
HIGH GRADIENT MAGNETIC
SEPARATOR

In the adsorption mechanism, magnetic seed can both adsorb to larger particles and act as an adsorbent for smaller particles in the water. Adsorption of smaller particles to magnetite used as the magnetic seed has been demonstrated in the concentration of viruses by high gradient magnetic separation*(2). The mechanisms of adsorption are not known but postulated mechanisms include chelation, as is probably the case with humic acid derived colorants, and poly or covalent surface bonding, which is likely in the adsorption of bacteria and viruses. Other mechanisms are possible.

The more versatile and more practical technique is chemical coagulation of the magnetic seed and contaminants into aggregates. Coagulation using an Al^{+3}, Fe^{+3} or Ca^{+2} coagulant generally will result in the production of somewhat fragile aggregates. These can be very successfully removed by high gradient magnetic separators under low shear force conditions (low unit flow rates). When an organic polyelectrolyte coagulant is also added, the interparticle bridging provided by the polyelectrolyte greatly strengthens the aggregates. Flocs produced by metal ions and polyelectrolyte coagulants will withstand high shear forces inherent in high processing rates.

* Personal Communication, T.A. Metcalf, Chairman, Dept. of Microbiology, University of New Hampshire

APPLICATIONS OF HIGH GRADIENT MAGNETIC SEPARATION TO WATER TREATMENT

Suspended Solids Removal

Steel Mill Waste and Process Waters--

Treatment of steel mill waters involves the direct filtration of finely divided, strongly magnetic suspended solids. Non-magnetic suspended contaminants such as tramp oil are naturally seeded by the magnetic particles. As a result, they are also removed without the addition of further seed or chemical media.

Table IV-1 presents some of the results obtained in treating steel mill process and waste waters(9). Sala Magnetics, Inc., has built a 500 gpm pilot plant for this application.

Other--

High gradient magnetic separation has many other applications to suspended solids removal. Treatment of boiler feed waters(10) and removal of radioactive corrosion products from nuclear reactor primary coolant loops (AECL-White Shell) are examples of direct filtration applications now in use. Seeded water treatment of municipal and industrial waste waters is of great potential importance in the removal of suspended solids as well.

Heavy Metals Removal

The release of heavy metals into the environment by industry or in agricultural practice poses both a health hazard to humans and causes extensive ecological damage. The hazard is especially great because the microflora are unable to excrete these pollutants which are consequently concentrated up the food chain. The efficient removal of heavy metals from point sources is of prime concern for the maintenance of pollution-free natural waters.

A process developed by Nippon Electric Company of Japan consists of treating waste water with ferrous sulfate, neutralizing with sodium hydroxide and oxidizing with air under specific conditions(11). As a result, a ferrite sediment in which the heavy metals and iron have been co-precipitated is obtained. This magnetic sediment is separated by magnetic filtration. The results obtained with this process are shown in Table IV-2.

The removal of heavy metals by precipitation and direct high gradient magnetic filtration has also been observed. Table IV-3 shows the removal of nickel and copper from precipitated plating waste waters by direct high gradient magnetic separation.

Bacteria Removal

Finely divided magnetite adsorbs well to bacterial cell membranes. When raw sewage, secondary treated effluent, or another polluted water is seeded with magnetite, the biomass is amenable to removal by high gradient magnetic separation(12,13,14).

TABLE IV - 1

Results Obtained Using High Gradient Magnetic Separation To Treat Steel Mill Process and Waste Waters(9)

	SUSPENDED SOLIDS		MAGNETIC	FLOW	NUMBER
	FEED (mg/l)	TREATED (mg/l)	FIELD (kG)	VELOCITY (m/min)	OF PASSES
BF Scrubber	1340	13	10	3.4	2
Water	582	1.2	5	1.32	2
Vacuum & Electric Furnace	309	2.5	10	2.1	2
BOF Scrubber	4500	<1	9.6	2.5	1
Water	4500	10	4.6	5	1
Hot Rolling	46	4	5	4.5	1
Mill Scale Pit*	168	12	2	4.5	1
Cold Rolling Mill Water	46.7	14	11.5	0.74	1

*Personal communication with John Harland, Sala Magnetics (1976).

TABLE IV - 2

Concentration of Metal Ions in Influent and Effluent(11)

Metal	Influent (mg/1)	Effluent (mg/1)
Hg	7.4	0.001
Cd	240	0.008
Cu	10	0.01
Zn	18	0.016
Cr	10	> 0.01
Ni	1000	0.2
Mn	12	0.007
Fe	600	0.06
Bi	240	0.1
Pb	475	0.01

TABLE IV - 3

Treatment of Plating Waste Water*

Sample	Cu (mg/1)	Ni (mg/1)	Treatment	pH
Feed	3.0	5.3	---	--
S-5	0.30	1.5	100 mg/1 $FeCl_3$	8.5
S-7	0.23	2.8	200 mg/1 Magnetite	8.5
S-8	0.16	0.85	No Additives	10.1

---

* Sala Magnetics' Data

Mitchell and co-workers(14) described a removal of between 90 and 99% of the bacteria from polluted water seeded with magnetite and passed through a high gradient magnetic filter. More recent studies in Mitchell's laboratory have yielded 99.9% removal of bacteria from seeded raw sewage.

Algae Removal

Algae are removed by high gradient magnetic separation as efficiently as bacteria. In batch experiments all of the algal cells in contaminated water were caught on the high gradient magnetic filter(1). The high degree of efficiency in removing algal cells probably reflects their large size and therefore the high concentration of magnetite adsorbed to their surfaces.

Virus Removal

Bitton and Mitchell(2) have carried out an extensive study of magnetic separation of viruses from water. Ninety-five percent of the viruses were removed by high gradient magnetic filtration following ten minutes of contact time with magnetite. A concentration of 250 mg/l of magnetite was sufficient to yield maximal removal. The addition of calcium chloride as a bridge between the virus and magnetite improved separation. The process provides 100% removal for as few as 30 and as many as 14,000 virus units (PFU) per ml of water.

Recent unpublished data from Bitton's laboratory show the efficiency of removal of polio virus using a SALA-HGMF™ virus concentrator. Table IV-4 shows these results. Between 99 and 100 percent removal of polio virus was achieved using high gradient magnetic separation.

Similar results have been obtained by Metcalf at much higher concentrations of polio virus. The enclosed letter (Table IV-5) indicates that he found high gradient magnetic separation to be very efficient in the removal of polio virus from water.

Dissolved Phosphorus Removal

Several methods are available for the removal of phosphorus from sewage. They depend on the coagulation of the phosphates with lime or alum. The coagulated phosphates are usually sedimented in ponds. Disadvantages of the sedimentation process include the requirement of time and space and the inability to remove finely suspended particles. By comparison, high gradient magnetic separation of phosphates is very rapid and removes even very finely suspended phosphate precipitates with systems requiring a small area(15).

Color and Turbidity Removal

Both colored materials and suspended solids associate well with magnetite making them amenable to removal by high gradient magnetic separation. Sala has carried out a series of bench tests on several pulp and paper mill effluents for a major U.S. paper company with excellent results. These results show significant reductions in color and turbidity.

TABLE IV - 4

Removal of Polio Virus from Water Using High Gradient Magnetic Separation

Feed Virus Concentration in PFU/ml	Removal Efficiency (%)
1025	100
1300	99
1250	100

The magnetite concentration in these bench tests was 1000 mg/l. $CaCl_2$ was used as a binder.

Data courtesy of Professor G. Bitton, Department of Environmental Engineering, University of Florida.

UNIVERSITY OF NEW HAMPSHIRE
DURHAM, NEW HAMPSHIRE 03824

TABLE IV-5

COLLEGE OF LIBERAL ARTS
Department of Microbiology
Spaulding Life Science Building

March 18, 1976

Mr. Don Dallas
Sala Magnetics
169 Bent Street
Cambridge, Massachusetts 02138

Dear Mr. Dallas:

Magnetic separation of virus from aqueous suspensions using permanent-type magnets (MIT model borrowed from David Kelland, and Sala Magnetics 2 kilogauss model) has proven technically feasible in studies carried out in the Virus Laboratory, University of New Hampshire. Studies using poliovirus type 2, have demonstrated the ability of these magnets to remove magentite-adsorbed virus within steel wool matrices subject to the magnetic force field. Imposition of appropriate parameters of pH, magnetite concentration, adsorptive conditions, steel wool matrices, magnetic field intensity and flow rates can result in complete removal of up to 1×10^6 plaque forming units of virus from 1 liter volumes under controlled laboratory conditions.

My current major interest in magnetic separation technics concerns their application to the recovery of enteric viruses from wastewater samples. This calls not only for an initial removal of virus from wastewater but also a subsequent recovery of virus from the steel wool matrix within the magnetic force field. Research goals currently are addressed to two fundamental objectives. The first is how best to efficiently and economically remove virus from large volumes of dirty wastewater, entrapping virus within collecting matrices. The second relates to a determination of conditions productive of a maximum recovery of virus from collecting matrices.

Study data suggest that magnetic separation technics can be applied successfully to the removal from relatively clean waters of at least the enteroviruses. There is no obvious reason at the moment to doubt the ability of the separation technology to cope successfully with other members of the enteric viruses also although I personally have not looked at any virus other than poliovirus. There are many details to be determined of course for waters of varying composition and quality, and I am not prepared to comment on removal efficiency but I do believe the technology is sufficiently promising at the moment to justify further research.

Sincerely yours,

T. G. Metcalf
Professor of Microbiology

OBJECTIVES OF THE STUDY

The objectives of this study were to:

1. Optimize the conditions for the removal of solids from combined storm overflows using bench-type tests.
2. Demonstrate effectiveness of a pilot scale high gradient magnetic separation treatment system for treating combined sewer overflows and storm water and to use this information as a basis for larger scale design.
3. Develop basic design criteria and operating characteristics for this system that can be translated into a larger scale.
4. Determine projected capital and operating costs based on the demonstrated treatment system.
5. Investigate the feasibility of high gradient magnetic separation systems for integrated wet and dry weather systems.

SECTION V

EXPERIMENTAL DESIGN

BENCH TEST APPARATUS DESIGN

The basic concept in bench testing is to use a simple jar test (modified by adding seed and flocculation steps) which can be used to set operational parameters for larger systems. The installation used in initial testing is shown in Figure V-1. A SALA-HGMS magnetic separator Model 5-18-2 identical to that in the continuous pilot plant was used. Backflushing was accomplished using line pressure (50 psig) tap water.

CSO samples were placed in 2-liter beakers and stirred with a paddle stirrer used in standard jar testing. Flocculated samples were poured into the funnel at the separation system top and routed through the pre-flooded high gradient magnetic separator. Testing showed that a 1.6 liter sample was too small to yield consistent, accurate results.

The bench test apparatus was modified to accept much larger samples. A 20 liter hopper was substituted for the original 2 liter funnel. The hopper was also raised from 40 cm to 55 cm above the high gradient magnetic separator. Since sample sizes up to 20 liters were to be used, the paddle stirrer was no longer sufficient and a variable speed stirrer was substituted. A platform had to be built to allow the transfer of these samples from agitator to hopper. This redesigned bench installation is shown in Figure V-2. The modified bench test system has been entirely adequate for all evaluations attempted.

PILOT PLANT APPARATUS

Design

The pilot plant used in these tests and owned by Sala Magnetics, Inc., is shown in Figures V-3, V-4 and V-5. It was designed and constructed at SMI expense to investigate the seeded water treatment technique.

The process flow sheet for the continuous pilot plant is shown in Figure V-6. As indicated in the flow sheet, the pilot plant contains a flocculation train in which all necessary chemical additions are made, a SALA-HGMS magnetic separator and power supply, and a surge tank and thickener to handle the backflushed flocs that were trapped in the matrix bed. An automatic controller sequences the addition and mixing of chemicals, water movement from tank-to-tank, and the actual filtration and backwash

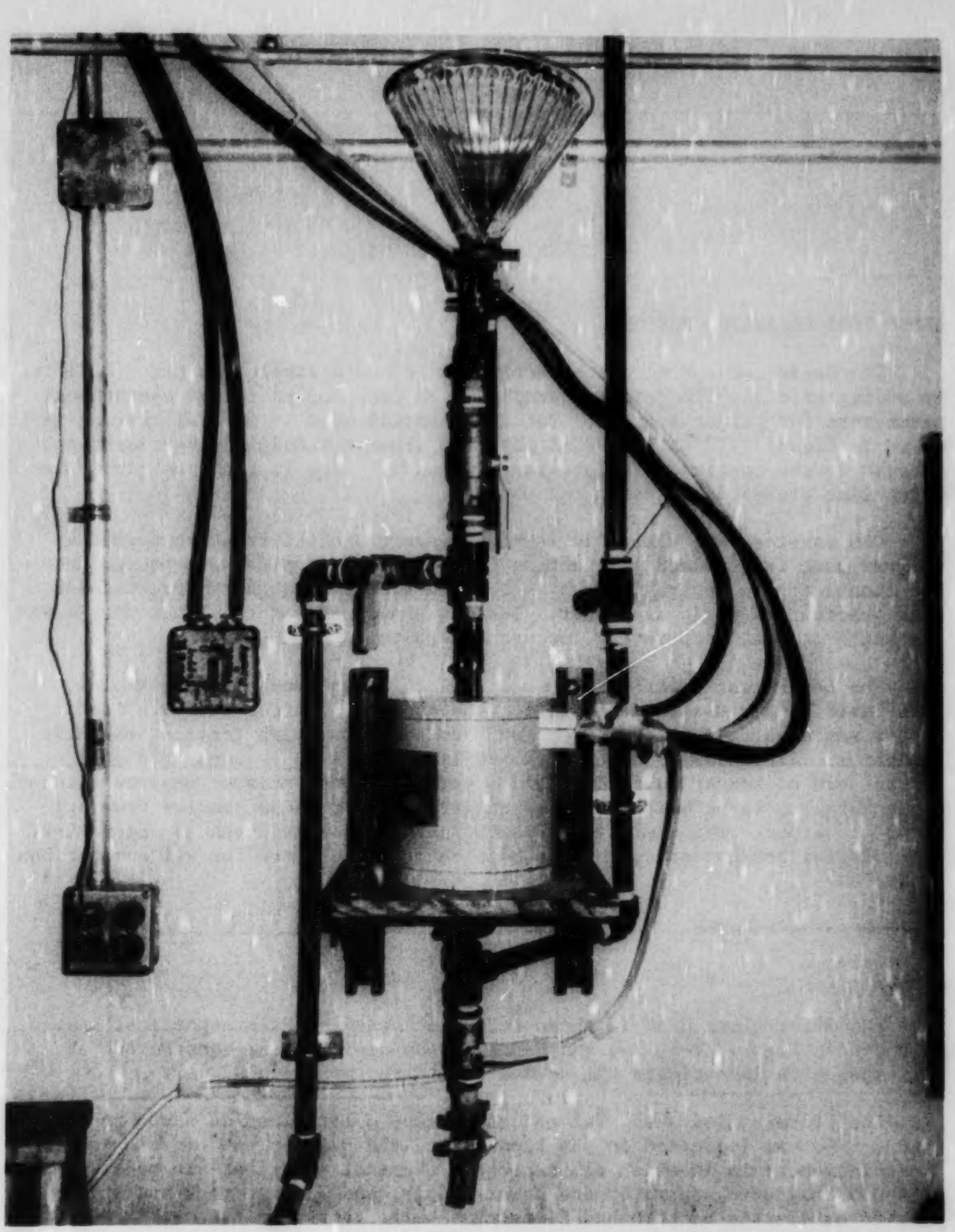


FIGURE V-1 INITIAL BENCH TEST APPARATUS

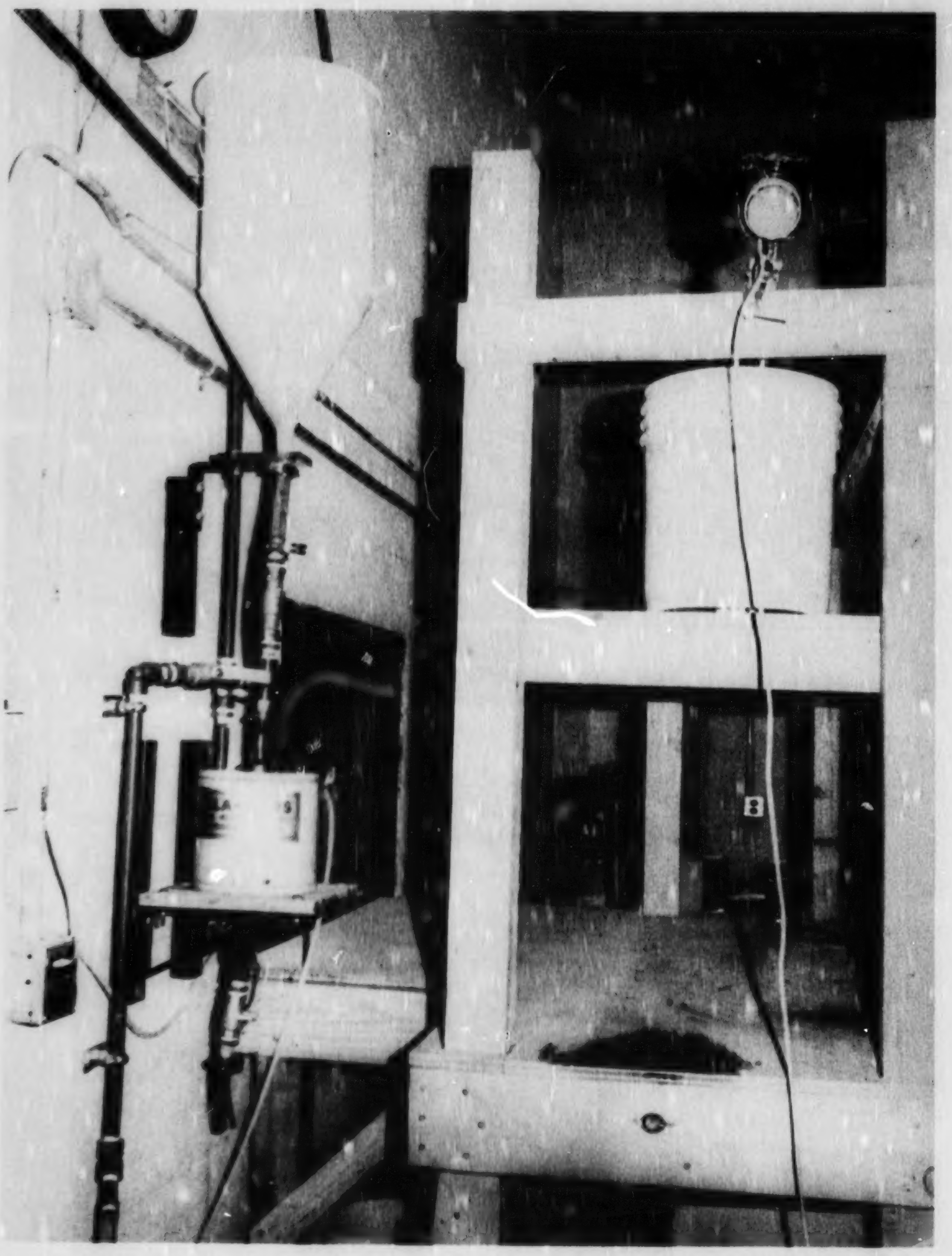


FIGURE V-2 REDESIGNED BENCH STUDY INSTALLATION

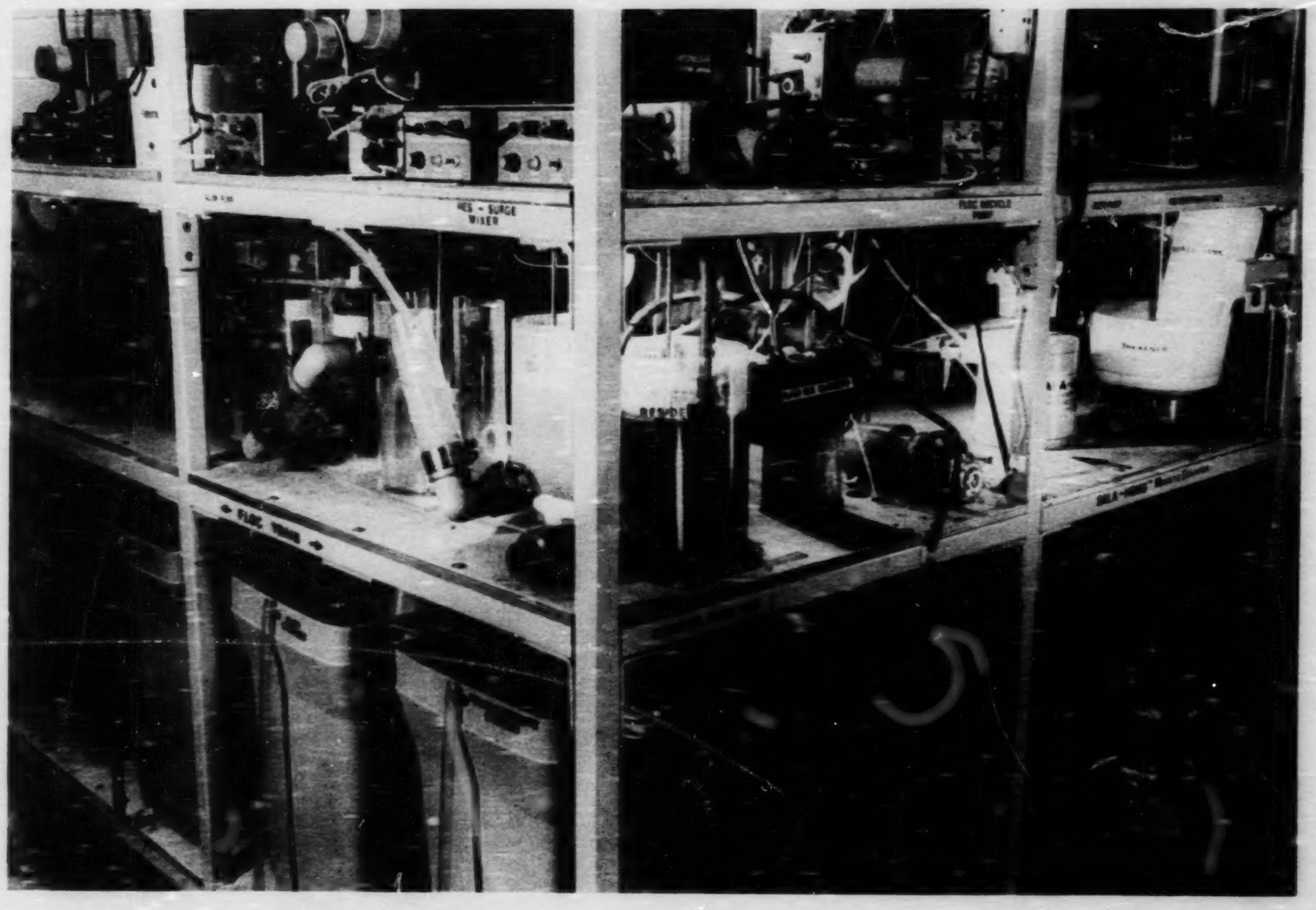

RES - SURGE MIXER
FLOC TANK
FLOC RECYCLE PUMP

FIGURE V-3 SALA CONTINUOUS PILOT PLANT

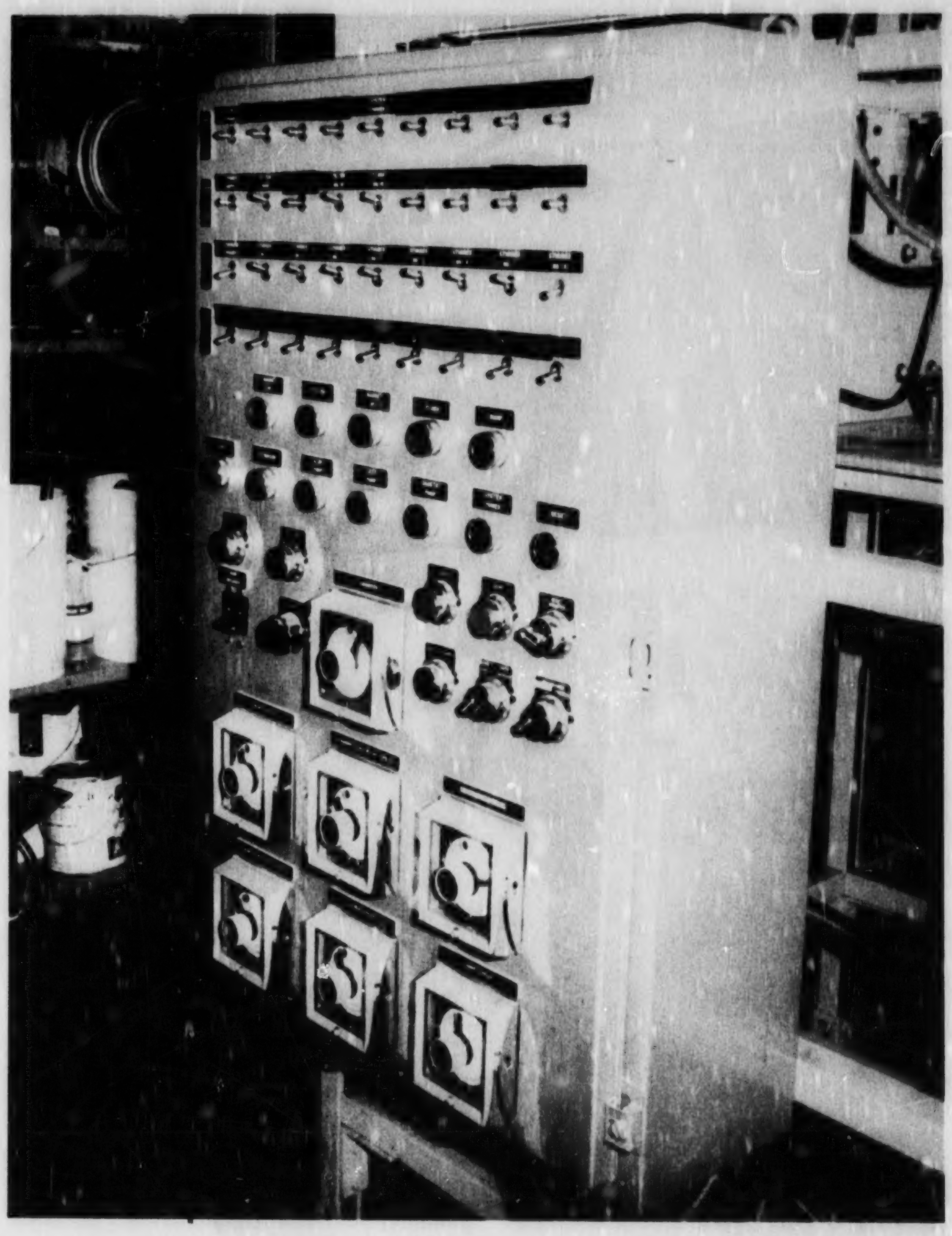


FIGURE V-4 PILOT PLANT AUTOMATIC CONTROLLER

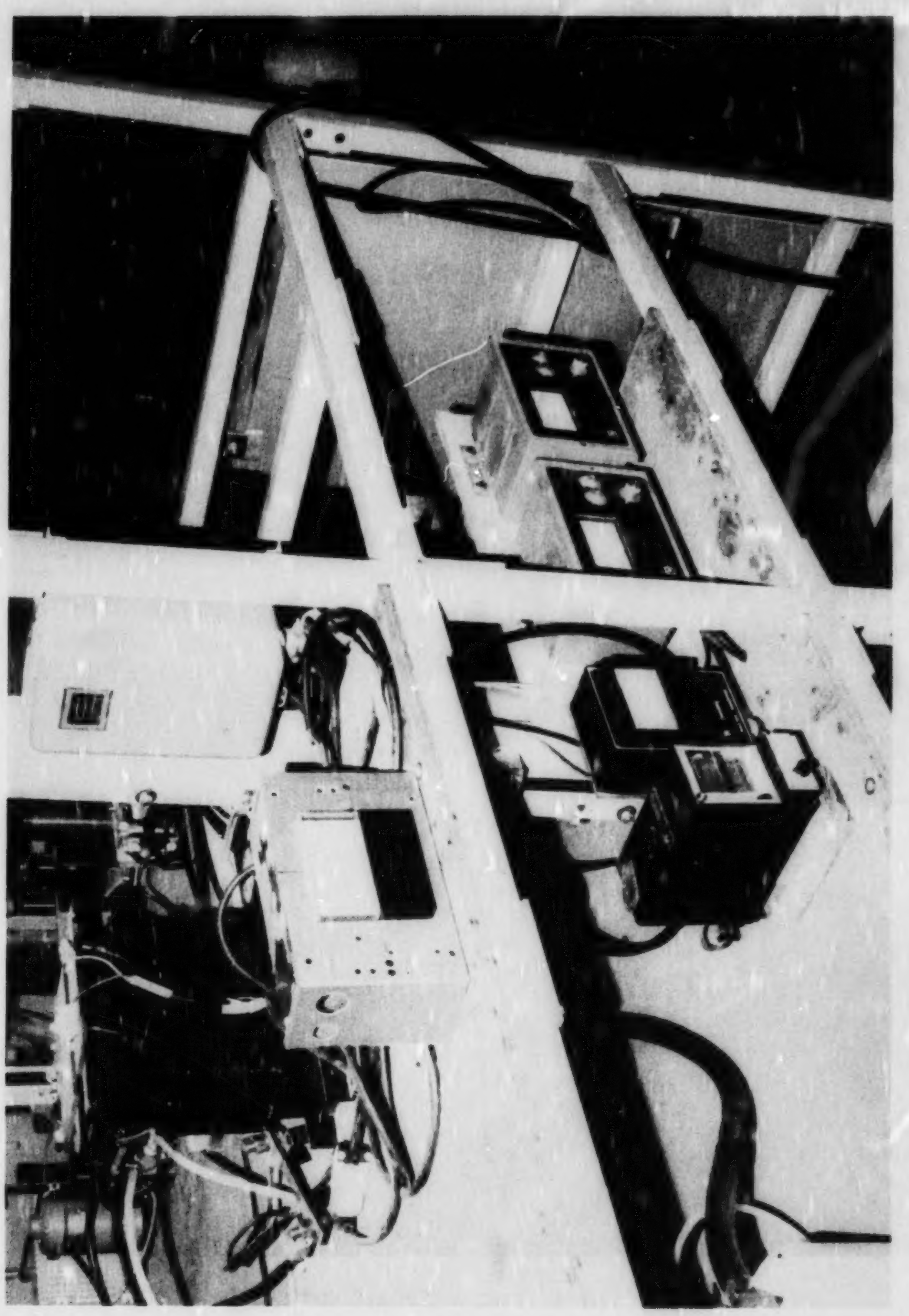
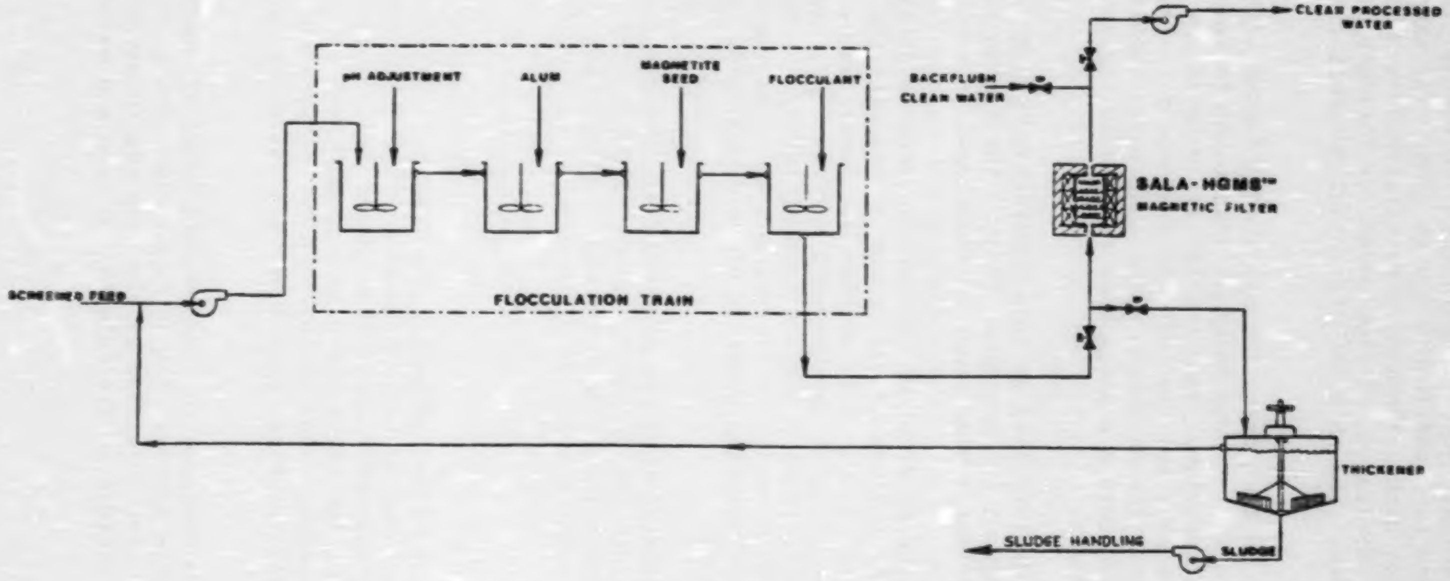


FIGURE V-5 PILOT PLANT POWER SUPPLY AND MONITORING SYSTEM


SCREENED FEED
pH ADJUSTMENT
ALUM
MAGNETITE SEED
FLOCCULANT
FLOCCULATION TRAIN
BACKFLUSH CLEAN WATER
SALA-HGMS™ MAGNETIC FILTER
CLEAN PROCESSED WATER
THICKENER
SLUDGE
SLUDGE HANDLING

PLANT CAPACITY: 240 LITERS PER HOUR
(1 GPM)

FIGURE V-6

FLOW SHEET

Seeded Water Treatment Pilot Plant

cycles through the magnet. Untreated feed is pumped from the storage tank to the first residence tank where the feed is mixed with alum. The magnetite is added in a second flash mixing tank. Finally, a polyelectrolyte is flash mixed into the stream to induce bonding among floc particles, bridging them together into larger agglomerates. The pH is monitored and controlled automatically.

The flocculated feed water is next drawn through the SALA-HGMS high gradient magnetic separator by a filter pump which is located downstream from the magnet to avoid floc disruption. Once the filter cycle is completed the filter pump and the magnet are shut off and the matrix is backflushed with high pressure water. The backflush water containing the flocs washed from the matrix filter bed enters a surge tank from which the integrated flow is fed to the thickener.

The pilot plant system is synchronized so that concentrations of chemicals remain constant throughout the residence chain. The system is easily adjusted, moreover, to permit a wide range of additions.

Initial testing of CSO on the pilot plant resulted in several problems. The most significant of these was failure of the valves controlling the flow to the high gradient magnetic separator. This problem was corrected by the installation of diaphragm valves rated to the intended service. Clogging of flow regulating valves was eliminated by 3 stage screening (final stage, 20 mesh) of the influent. Proper metering of flocculants and seed was ensured by the installation of adjustable metering pumps in place of constant level tanks.

Bench test experiments indicated that the magnetite and polyelectrolyte additions would be flash-mixed into the influent stream. Flash-mixing chambers were installed just before the residence surge tank. During operation certain components of the pilot plant were discovered to be unnecessary and were eliminated.

Flexibility and Capacity

Pilot plant operation may be either manually or automatically controlled. In the automatic operational mode nearly any combination of filter cycle and backflush can be obtained. The automatic controller is partially interfaced with process monitoring equipment (pH controller and turbidimeter) and responds to feedback from those sources. Thus the pilot plant can monitor the effluent quality and automatically initiate backflush once filtering capacity of the matrix is reached.

Because the pilot plant was designed to study seeded water treatment, it was constructed as a very flexible system. The influent flow rate is varied by valve adjustment. Residence time is varied by changing the number of tanks in the floc chain. The concentrations of flocculants and seed are easily adjustable over wide ranges.

SECTION VI

METHODS AND PROCEDURES

BENCH TESTS

Test Procedures

The tests performed in the bench study were essentially modified flocculation jar tests. The flocculants and seed were added to the CSO samples while stirring at 200 RPM with a paddle stirrer. Subsequently the mixer speed was reduced to 90 RPM for the duration of the flocculation. In these tests, the alum was added first followed by the magnetite seed and polyelectrolyte.

After flocculation occurred, the sample was transferred to the funnel feeding into the SALA-HGMS magnetic separator. The matrix volume was kept full of clean water at the beginning of each bench test so as to ensure uniform flow velocity through the matrix. The first matrix volume of water (clear water in matrix at start) to come out of the high gradient magnetic separator was discarded. The treated CSO was then tested to determine remaining suspended solids, turbidity, etc.

Scope of Testing

A parametric study was carried out to determine the initial operating conditions for the continuous pilot plant. The following parameters were varied over the ranges listed below:

1) Applied Magnetic Field: 0.1 to 1.95 kG
2) Flow Velocities: 60 to 300 m/hr
3) Alum (commercial grade) Concentration: 0 to 200 mg/l
4) Seed: commercial grade Magnetite (Fe_3O_4)* Concentration: 50 to 5000 mg/l
5) Polyelectrolyte (Betz 1150) Concentration: 0 to 3.0 mg/l

* Magnetite obtained from Eveleth Taconite Co., Eveleth, Minn. This was sized, washed and deslimed before use. Size classification chosen was +5μ -40μ. This procedure included discarding the fraction larger than 325 mesh (>40μ), putting ore into a slurry form and decanting the top portion after 90 minutes.

6) pH (adjustment by NaOH, HCl reagent grade): 4.5 to 7.5

7) Residence Times: 1 to 10 minutes

All samples were analyzed for suspended solids, apparent color and turbidity. It was originally intended that all samples be analyzed for settleable solids; however, these were always immeasurable in the treated samples. Selected samples were analyzed for filtered and unfiltered BOD_5 and COD, fecal and total coliform and certain trace heavy metals.

PILOT PLANT

Test Procedures

The following procedures were performed during testing on the continuous pilot plant. Initially, seeded flocculation jar tests were run to determine the approximate dosages of alum and polyelectrolyte. Flow rates of flocculants and seed were adjusted to achieve the desired concentrations. The influent and effluent flows were then set at the desired rates.

The flocculation residence chain was allowed to stabilize before testing was begun. Thirty minutes of operation were generally allowed to achieve stabilization although visually the system seemed stable after 8 minutes. In addition, twelve minutes or more were allowed for stabilization between parameter changes. Samples were taken at various points in the filtering cycle depending upon the test being performed. Samples were then analyzed.

Scope of Testing

The following tests were performed on the continuous pilot plant:

1. Alum, seed and polyelectrolyte concentrations were varied to compare cost as a function of performance.

2. Matrix loading was varied to determine effective filter cycle length.

3. Residence times were varied to evaluate system effectiveness over a range of residence times.

4. Raw sewage was treated to determine the feasibility of using high gradient magnetic separation for treatment of both wet and dry weather flows.

5. Magnetic field and flow rate were simultaneously increased to determine the system's ability to maintain performance level at increased capacities needed in the case of storm surges and overflow.

ANALYTICAL PROCEDURES USED IN BENCH AND PILOT TESTING

All analyses were performed according to the analytical methods listed below:

	Units
Suspended Solids (Nonfiltrable Residue) - Standard Methods #224 C	mg/1
Turbidity - Standard Methods #163A	FTU
Color, Apparent - STORET No. 00080	PCU
Settleable Solids - Standard Methods #224 F	ml/1
BOD_5 - Standard Methods #219, Probe Method	mg/1
COD - Standard Methods #220	mg/1
Fecal Coliform - counts on EMB agar at 37°C	# cells/100 ml
Heavy metals - Cd, Pb, Zn, Cr, Ni, Hg, Cu	mg/1

SAMPLE COLLECTION

For most of the bench testing work the CSO was collected in five gallon buckets, up to 60 gallons at a time. This collection method worked well for the bench test phase as sealed buckets could be transported easily and samples could be taken at short notice.

When testing was initiated on the continuous pilot plant much larger sample volumes were required than could be reasonably collected in buckets. Sampling was arranged with a local septic tank pumping firm. The firm* used a 1500 gallon vacuum truck with the agreement that the truck tank be rinsed with hydrant water several times before collection. This large sample was discharged into 2 large storage tanks (Figure VI-1) equipped with agitation, aeration and ventilation.

During the course of testing it was discovered that the CSO collected by the septic tank truck was severely contaminated in spite of the tank rinsing. Examination of the tank interior showed that a contaminated sample would be unavoidable. While the septic tank truck drew a sample, a bucket sample was taken simultaneously. Comparisons of the two samples, presented in Table VI-1, showed that severe contamination had resulted from the truck. After this test all subsequent samples were collected in clean 55 gallon drums using a portable pump.

One problem that was both anticipated and encountered, was significant biological growth during storage. In one case (CSO of 12/9/75, Table A-1) the suspended solids in the feed doubled in 7 days. Since excess biological

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* Clearway Sewerage and Drain Service, Inc., Cambridge, MA

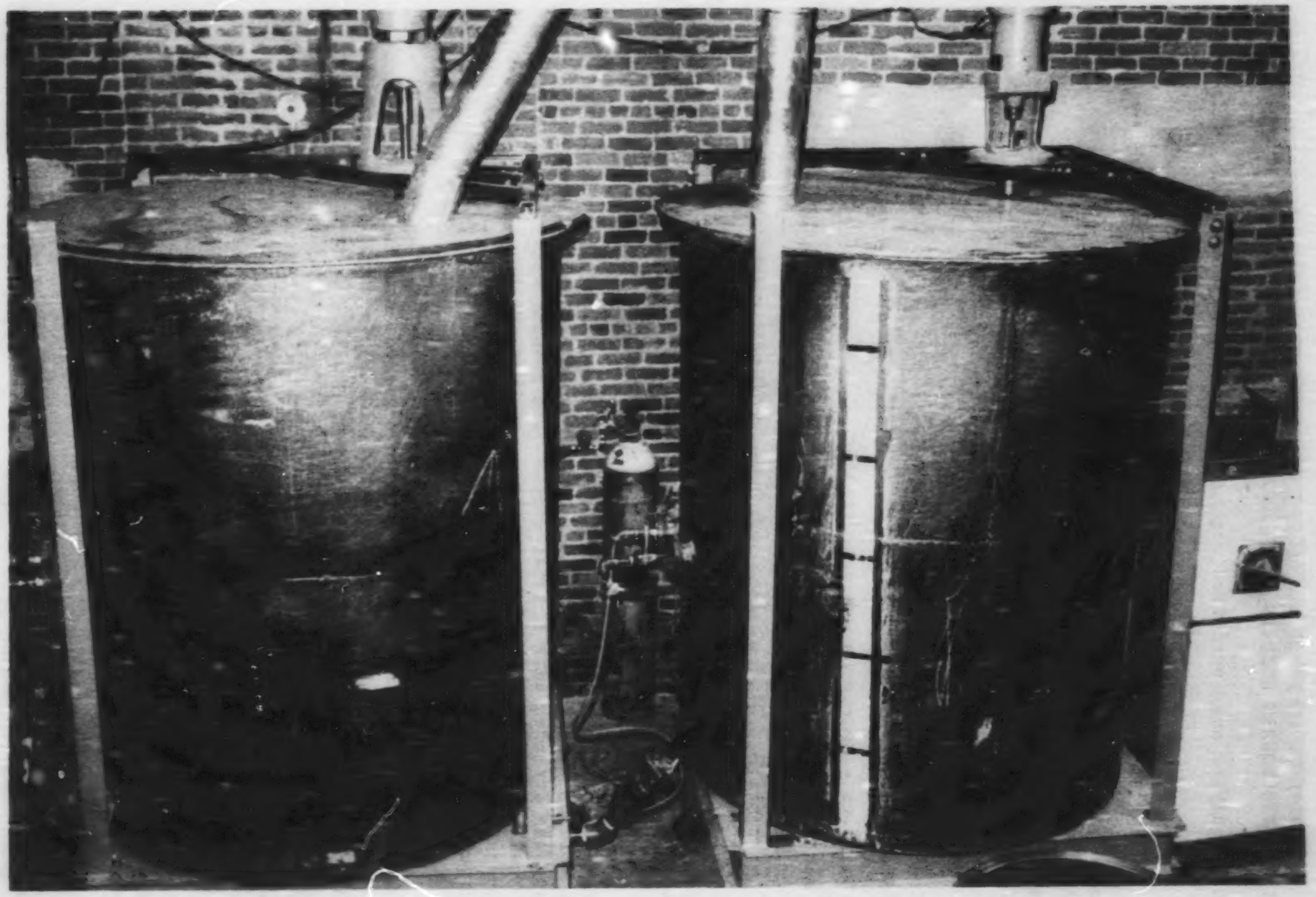


FIGURE VI-1 STORAGE TANKS FOR CSO SAMPLES

TABLE VI - 1

COMPARISON OF METHODS OF COLLECTION

CSO COLLECTED ON 1/14/76

	SUSPENDED SOLIDS (mg/1)	APPARENT COLOR (PCU)	TURBIDITY (FTU)	FECAL COLIFORM	TOTAL COLIFORM
				(cells/100 ml)	
Feed from Truck*	415	1130	350	2.7×10^6	1.6×10^8
Feed from Bucket**	36	120	32	9.3×10^5	7.7×10^6

---

* Septic tank pumping truck, after being rinsed several times with hydrant water, collected a 4000 liter sample of CSO from Cottage Farm.

** A small sample of CSO was collected in buckets simultaneously with septic tank pumping from same point to check contamination levels of truck collection.

digestion tends to result in a more easily flocculated feed, extended storage times were avoided. Aeration was necessary to keep the sample from becoming anaerobic and thus producing a methane safety hazard.

ANALYTICAL LABORATORY FACILITIES

Sala Magnetics, Inc., has equipped and maintains an analytical laboratory (Figure VI-2) for water and waste analysis. The following tests (as described in Section VII) were performed in the SMI laboratory:

Suspended Solids
Settleable Solids
Color (Apparent)
Turbidity
BOD_5, Total
Fecal Coliform

The following tests were performed at outside laboratories:

COD
Heavy metals (quantitative)

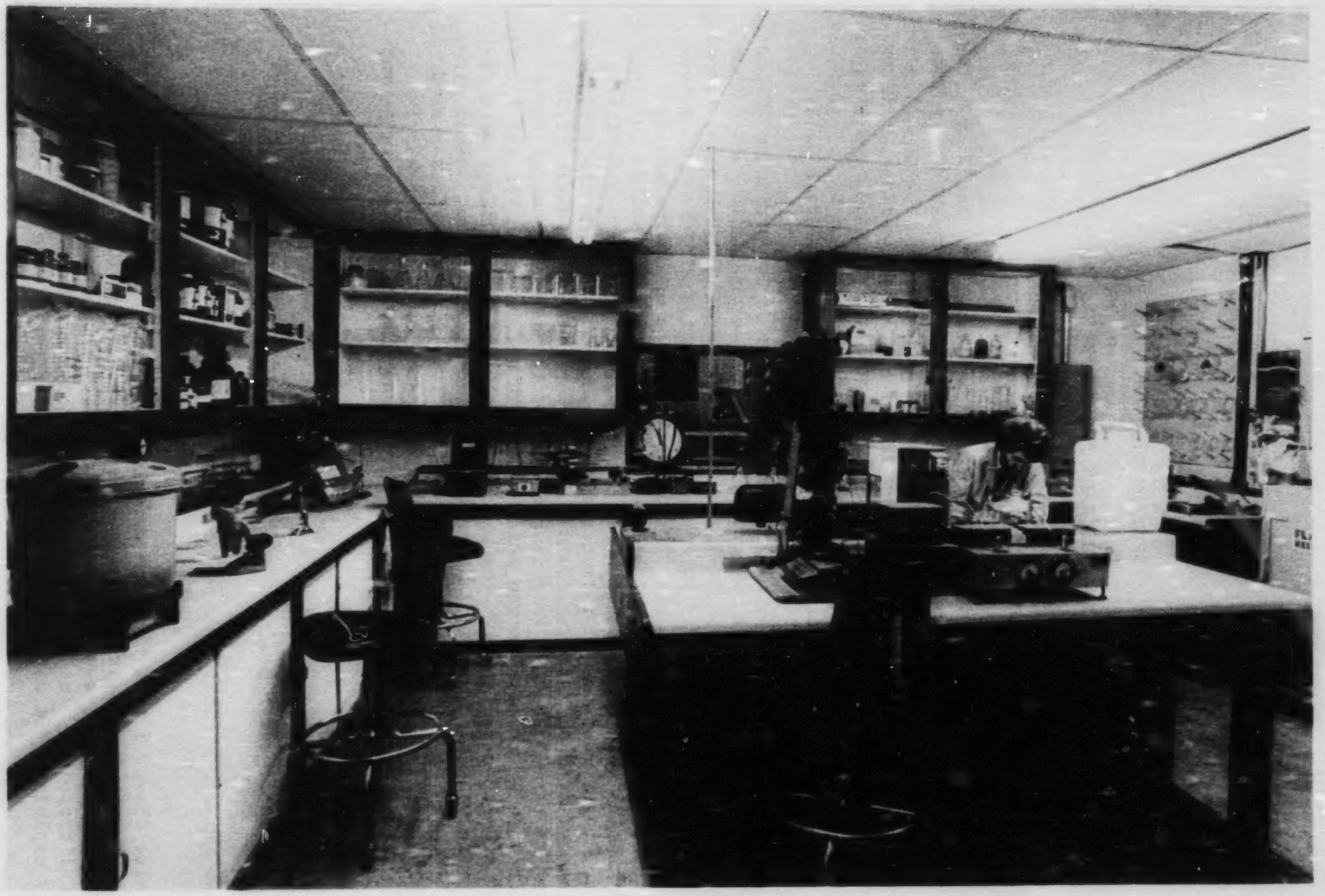


FIGURE VI-2 WATER ANALYSIS LABORATORY AT SALA MAGNETICS, INC.

SECTION VII

TESTING PROGRAMS PERFORMED

BENCH TESTING PERFORMED

On 12/9/75 a CSO sample was drawn from the Cottage Farm facility. The facility's activation was a small flow of short duration. Suspended solids in this CSO were very low and settleable solids were immeasurable. All parameters of the revised bench study were varied independently using 1.6 liter samples. Listed in Table A-1 are the combined results obtained from testing this CSO sample (without parameter optimization). Detailed data for this and other storms are contained in Appendix A and discussed in Section VIII.

Due to both the low suspended solids loading in this particular CSO batch and the sample size used, the magnetic filtration matrix loading was rather low (0.012 g/g matrix fiber). At this low matrix loading, mechanical trapping could contribute significantly to the actual filtration efficiency. A test conducted at zero magnetic field showed that a sample of approximately 5 liters was required to minimize these effects. At this low solids loading several samples were flocculated under identical conditions in 1.6 liter aliquots. These were passed in succession through the high gradient magnetic separator set at 0 kG magnetic field. Since there was no magnetic field operating to retain seeded flocs in the matrix, the degree to which flocs were mechanically trapped in the matrix could be determined. For the first liter of sample passed through the matrix, nearly all of the flocs were retained by mechanical trapping. After two additional liters had passed, approximately 50% of the flocs were caught. Nearly all of the flocs passed through the matrix after feeding 3 to 3.5 liters of sample. The matrix loadings after passing the aforementioned volumes through the separator magnet are listed below:

	Volume	Matrix Loading
Flow Velocity of 120 m/hr	1 liter	0.007 g/g matrix
	2	0.015
	3	0.023
	5	0.035

It was also observed that the flow velocity used had a large effect on floc retention due to mechanical trapping. At low flow rates (120 m/hr or less) this trapping was most severe. Higher flow rates showed reduced levels of mechanical trapping. The relationship of hydrodynamic drag forces to flow velocity explains this variation. Subsequent jar tests were run with sufficiently large samples to get satisfactory matrix loadings (0.03 g solids/g matrix fiber).

On 12/19/75 a small CSO sample was collected from Cottage Farm to verify the performance of high gradient magnetic separation treatment at higher matrix loadings. The combined results obtained from this testing are listed in Table A-2. Matrix loading reached 0.16 g solids/g matrix in this test, a loading high enough to render mechanical trapping a negligible part of the actual filtration.

Pump failure at Deer Island Sewage Treatment plant resulted in Cottage Farm handling raw sewage on 12/26/75. A limited evaluation of the SALA-HGMS Magnetic Separation Water Treatment System was conducted on this sewage; the combined results are tabulated in Table A-3.

Melting snow on 12/31/75 caused activation of the Cottage Farm facility; and a 700 gallon sample was taken. Flow velocity and magnetite concentration were varied. Bench treatment of this CSO has yielded the combined results shown in Table A-4. It should be noted that the melt waters tested (samples of 12/31/75 and 3/17/76) were both heavily laden with solids and bacteria. In both cases exceptionally good magnetic purification was possible, indicating the high gradient magnetic separator's ability to deal with such highly polluted waters in a single pass through the magnet.

On 1/28/76 a small sample (40 liters) of CSO was collected from Cottage Farm. Bench tests were conducted using a 1.0 kG permanent magnet on 4 liter samples. Since the effective length of this separator was only 3 inches (compared with 6½" for our electromagnets) this small sample size was sufficient to provide satisfactory matrix loading (0.03-0.11 g solids/g matrix fiber). A series of 9 aliquots were tested, 3 data points each for magnetite seed, alum and polyelectrolyte concentrations. The results are shown in Table A-5. The lower removal efficiencies compared to tests with electromagnets are attributed to the reduced magnetized matrix span through which the sample was passed. Flushing of this system was also more difficult and may have been a source of error (the canister had to be removed and hand flushed after each test).

On 3/1/76 a small sample of raw sewage was collected from Deer Island Sewage Treatment Plant. Bench tests were performed on this sample to find optimum pH ranges for an alum - polyelectrolyte concentration ratio of 50:3 on raw sewage (the test of 12/9/75 tested the effect of pH on CSO with alum to polyelectrolyte concentration ration of 60:1). The results of these tests are compared and plotted in Section VIII.

The final bench tests of this study were performed on Deer Island sewage collected on 3/8/76. Thirty gallons were collected for further testing of the interactions and effects of alum, polyelectrolyte and pH. Combined results are shown in Table A-8. Bacterial analysis of these tests showed excellent fecal coliform removal (99.4%).

Excellent bench test results were obtained using the high gradient magnetic separation treatment process. In overall bench study tests, the average removals for suspended solids, apparent color, turbidity and bacteria were 93, 85, 91 and 98% respectively. This performance exceeds that of conventional primary and secondary treatment systems.

CSO samples with both low and high solids loading were successfully treated. Suspended solids and turbidity were generally reduced to 10 mg/l and 10 FTU respectively, in spite of very high initial solids loading. Reductions to as little as 1.8 mg/l and 3 FTU were achieved.

The apparent color removal observed in these bench tests was considerably better than in conventional treatment processes. Most color in CSO is due to the presence of humic acids and humic-like materials. These chemicals are chelating agents which will complex with the iron added in the flocculation process. It is probable that this complexing process results in the formation of colored paramagnetic materials which can be easily removed by a high gradient magnetic separator.

Pilot Plant Runs

A 500 liter sample of raw sewage (the influent to primary treatment sedimentation tanks at Deer Island Sewage Treatment Plant) was collected on 1/29/76. After initial jar tests to determine optimum flocculant concentrations, a test program was run on the pilot plant. TableA-6 gives the combined results of all tests done on this raw sewage. It can be seen from these data that SALA high gradient magnetic separators are highly effective in treating this raw sewage in a continuous operation.

Tests performed to measure cycle to cycle consistency showed that less than 2% variation existed between stabilized four minute cycles. This is well within expected sampling contamination and analytical limits of error.

A 500 liter sample of CSO was taken from Cottage Farm on 2/2/76 for use in a pilot plant run. Magnetite seed concentration was varied from 50 to 800 mg/l using 4-minute cycles. A summary of the data from the 100-800 mg/l magnetite-concentration treatment is given in Table A-7. Breakthrough was encountered at a magnetite concentration of 50 mg/l. It should be noted that a relatively short residence time was necessary (3 minutes) and low polyelectrolyte and alum concentrations were used (1 mg/l and 50 mg/l respectively with this CSO sample), yet the removal efficiencies are high.

A snow melt of 3/17/76 caused activation of the Cottage Farm facility. Five hundred liters of CSO were collected for continuous pilot plant testing. Several discrete test sequences were run on this sample including polyelectrolyte and alum variation, matrix loading tests, surge simulation runs, magnetic field variation, and optimum parameter runs to obtain consistency and probability data. Combined data for these tests are given in Table A-8 and for the optimized run alone in Table A-9. Solids loading in this CSO was very high and separation efficiency by seeded water treatment was excellent resulting in very high percent removals for all contaminants measured. Suspended solids, apparent color, turbidity, fecal and total coliform bacteria, total BOD_5 and COD analyses were performed on these runs.

Excellent results have been achieved with the continuous pilot plant on both CSO and raw sewage. The level of performance obtained equals or exceeds that of bench or jar tests.

The high level of performance is attained with a flocculation train residence and filtration time of approximately three minutes, a fraction of the time required for flocculation and processing in conventional waste treatment systems. Additionally, there is an indication that, although the flocs formed are very small in size compared with those generally used for conventional settling or filtering, the flocs themselves are much less susceptible to physical disruption. There is also an indication that the addition of magnetic filter aid such as magnetite can reduce chemical reaction time to less than ninety seconds. This may be attributed, in part, to the fact that stirring during chemical additions in conventional jar tests is done at twenty (20) RPM while in Sala's bench test and pilot plant mixing is carried out at ninety (90) RPM. Additionally, there is evidence that without the addition of alum and a polyelectrolyte certain contaminants such as bacteria and viruses have an affinity for magnetite and may bond with it, increasing removal efficiency for these contaminants.

Pilot plant tests have indicated that highly reproducible results may be obtained in high gradient magnetic filtration of CSO and raw sewage. Cycle to cycle variations in performance have not exceeded two percent (2%) indicating the system's stability.

Seed concentrations needed relative to feed loadings were found to be much lower than previously reported, an exciting result in terms of seed cost and simplicity of the system (possible elimination of a seed recycle process). Of particular potential value is the ability of the high gradient magnetic separator to substantially reduce apparent color, biological contaminants (including both bacteria and viral pathogens) and trace heavy metals.

SECTION VIII

RESULTS AND DISCUSSION

INTRODUCTION

Experiments carried out on the pilot plant and bench apparatus were designed to test independently the following parameters and their interactions: alum, polyelectrolyte and magnetite concentrations, pH, magnetic field strength, flow velocity, residence time, and matrix loading. Evaluation of results was based chiefly on the analyses done on feed and treated samples for suspended solids, apparent color and turbidity. Fecal and total coliform counts were also performed on many of the samples. Selected treated and untreated samples were analyzed for COD, BOD_5 and trace metals.

Since the character of the waste water used during this study was very different for each storm or sewage sample collected, a wide range of "types" of wastes was encountered. Raw sewage of course differs from CSO. But even CSO as observed at Cottage Farm fluctuates tremendously in solids loading, etc. The time of year, time of the day, the amount of recent rainfall, the source of water (rain, snow, snow melt) and the duration of the storm, all affect the composition of the CSO. Likewise, raw sewage effluent varies a great deal.

It is of course advantageous to test a new process with the full range of waste waters to be encountered in a functional situation. But this also makes the comparison of results somewhat more difficult, since different initial feeds necessarily mean slightly different levels of separation efficiency in the purified product. In the graphs that follow, percent removal has been plotted against the parameters varied. Since each storm was different, optimal removal achieved in each testing series is not strictly comparable. Also, complete optimization of those parameters being held constant was not usually attempted. Nevertheless, the relationships shown are meaningful for all CSO and raw sewage treated by high gradient magnetic separation. The shapes of the curves are essentially constant, but the curves themselves may displace slightly depending on the degree of optimization and the type of water being treated.

INTERACTING CHEMICAL PARAMETERS

Alum

Alum $[(Al_2SO_4)_3]$ was used in all tests performed as the principal coagulant. Its concentration is a very important parameter for good separation, as without good flocs non-magnetic particles will not be removed by the magnet. The key to seeded high gradient magnetic separation is, above all, to flocculate a high percentage of the solids in the presence of magnetite. Once this is accomplished the flocs can easily be strengthened if necessary by an organic polyelectrolyte and removed by the high gradient magnetic separator.

Optimal alum coagulation is directly dependent upon a number of interrelated factors including pH, solids loading and character, and relative amounts and kinds of other flocculating agents used (polyelectrolyte in the present case). Optimum alum coagulation occurs at a pH of between 5.5 and 6.5 while polyelectrolyte flocculates best at around pH 8. Thus for CSO and raw sewage, where tests have shown that both a coagulant (e.g. alum) and a floc-strengthening agent (e.g. polyelectrolyte) are necessary, a compromise must be made between the two pH extremes. Since results show that this compromise is not detrimental to magnetic separator efficiency it may in fact prove to be advantageous, since the pH of CSO and sewage is usually close to 7 and amenable to this combination of chemical flocculants. It is thought that pH adjustment should be minimal or eliminated altogether when these flocculants are used in the proper proportions. Except for certain tests devised specifically to determine pH effects, all tests in this study were made at natural pH. The excellent results obtained show that alum-polyelectrolyte flocculation works well at normally encountered waste water pH values.

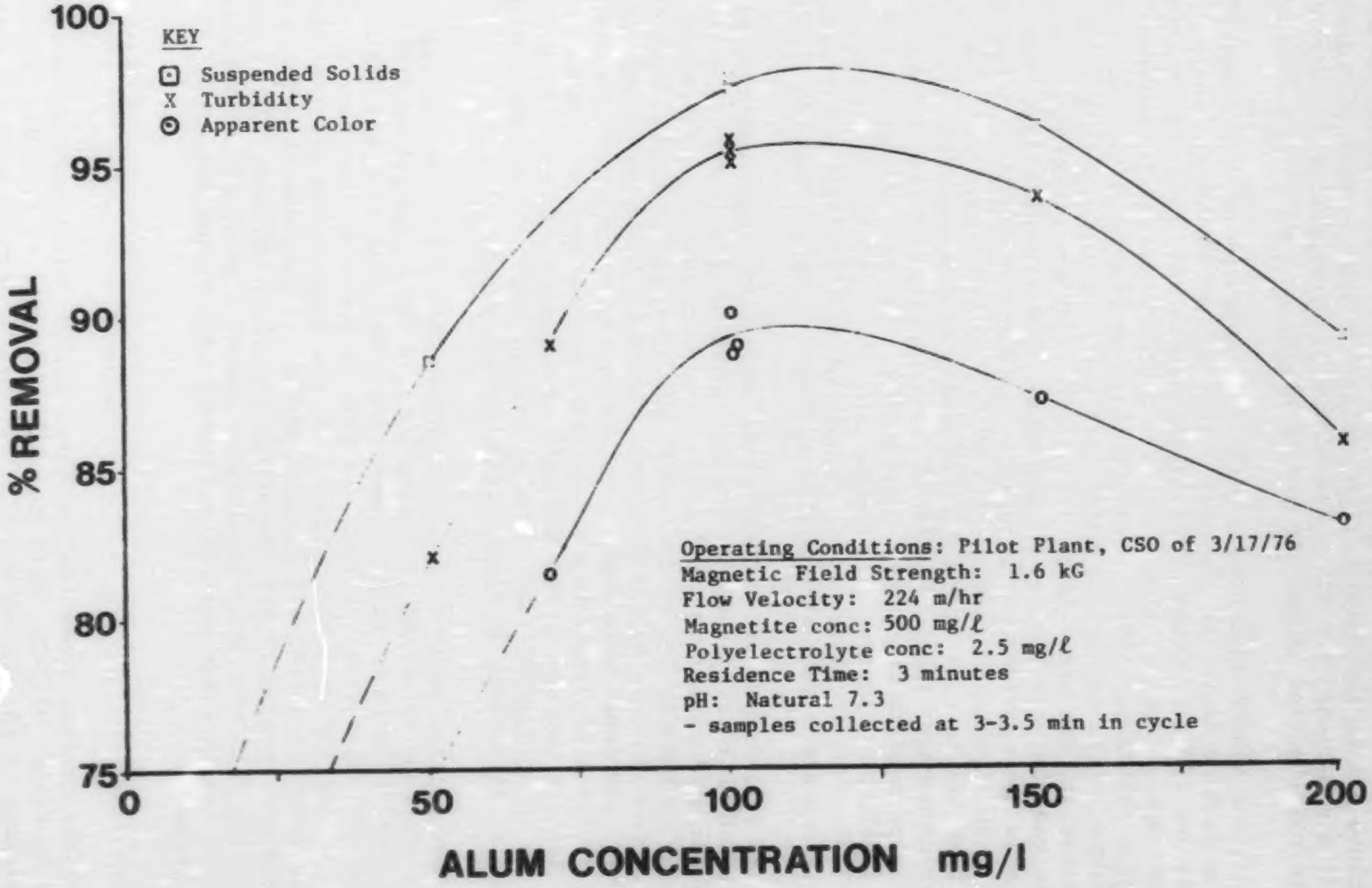
When polyelectrolyte concentration and pH are held constant, variations in alum concentration show that optimum flocculation (and consequently separation efficiency) is essentially dependent upon feed character. Generally, more heavily loaded influents require slightly higher alum concentrations than do less polluted waters. For each bench and pilot plant test performed, jar tests were made to determine the optimum alum concentrations necessary for good flocculation. The range encountered was rather narrow, always falling between 50 and 120 mg/l of aluminum sulfate, although as little as 10 mg/l difference for a particular waste water sample could make a substantial difference in flocculation effectiveness.

Figure VIII-1 shows alum concentration versus percent removal of suspended solids, apparent color and turbidity for the CSO collected on 3/17/76 and run on the continuous pilot plant. Operating conditions used are indicated on this and all subsequent figures. In this instance an alum concentration of between 90 and 120 mg/l was optimal. At the lower range of alum concentrations separation fell off rapidly, while the decrease in efficiency decreased more gradually for concentrations above optimum. Tests conducted without alum (and with polyelectrolyte) showed essentially no separation as flocs were very stringy and did not entrap significant amounts of the solids in the water.

Polyelectrolyte

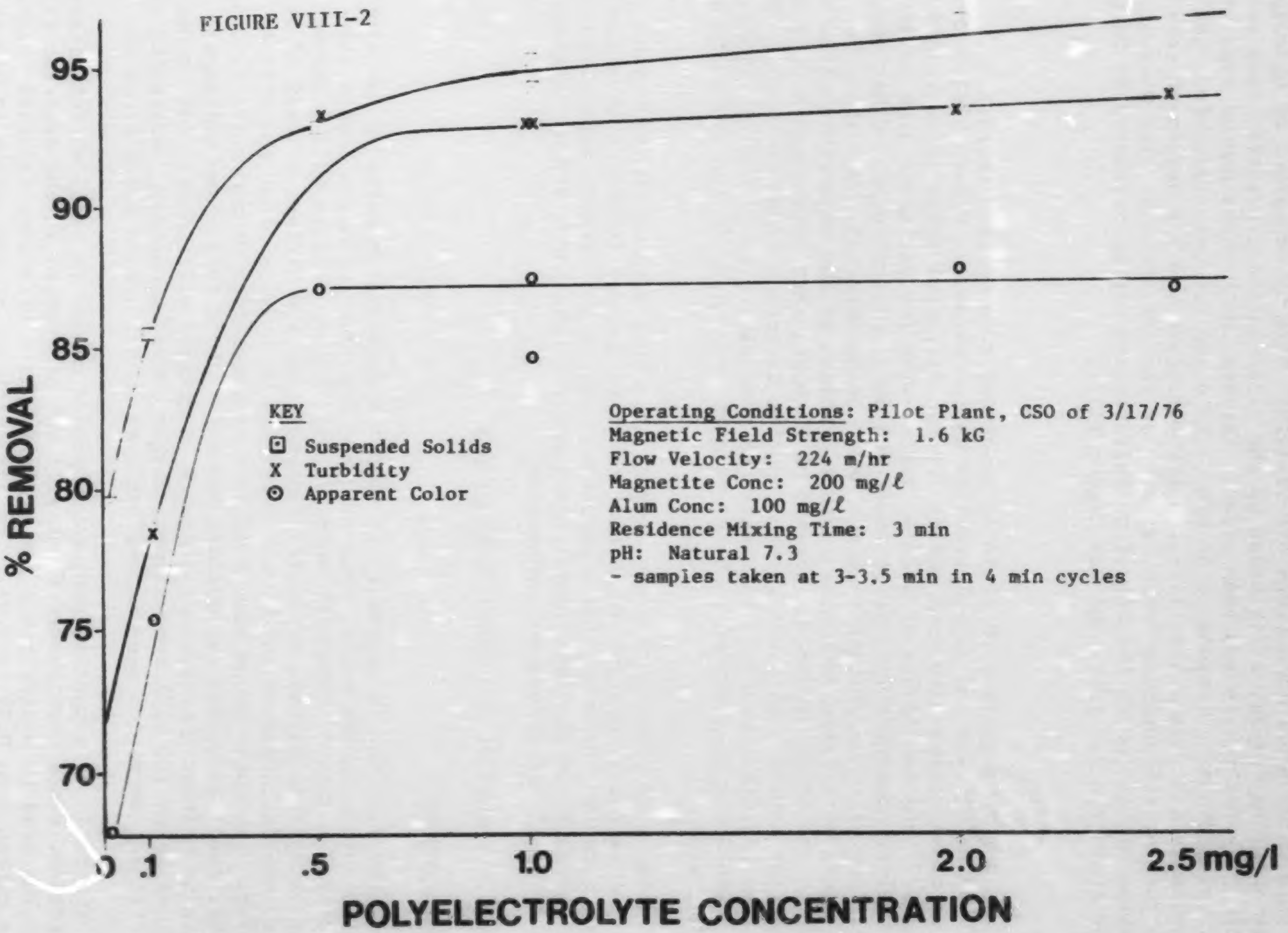
Polyelectrolyte concentration (Betz #1150) versus percent removal is plotted in Figure VIII-2. This graph is also derived from data obtained in the treatment of the CSO of 3/17/76. It can be seen from this figure that separation efficiency seems to reach an optimal plateau above a certain

FIGURE VIII-1



Operating Conditions: Pilot Plant, CSO of 3/17/76
Magnetic Field Strength: 1.6 kG
Flow Velocity: 224 m/hr
Magnetite conc: 500 mg/ℓ
Polyelectrolyte conc: 2.5 mg/ℓ
Residence Time: 3 minutes
pH: Natural 7.3
- samples collected at 3-3.5 min in cycle

FIGURE VIII-2



Operating Conditions: Pilot Plant, CSO of 3/17/76
Magnetic Field Strength: 1.6 kG
Flow Velocity: 224 m/hr
Magnetite Conc: 200 mg/ℓ
Alum Conc: 100 mg/ℓ
Residence Mixing Time: 3 min
pH: Natural 7.3
- samples taken at 3-3.5 min in 4 min cycles

minimum concentration of polyelectrolyte (in this case, about 0.5 mg/l). Below this value separation drops off rapidly. This is explained by hydrodynamic shearing forces, which break up the flocs inside the matrix when too little polyelectrolyte has been added. Earlier bench tests showed that when flow velocity was decreased to 56 m/hr, the curve for polyelectrolyte was essentially a straight line (i.e., polyelectrolyte was not needed at this flow rate as the shearing forces were below the threshold of floc disruption). Likewise higher concentrations of polyelectrolyte may be necessary at flow rates above the 224 m/hr used for Figure VIII-2.

pH

As described above, pH plays an important role in the separation achieved using alum and polyelectrolyte as flocculants. Figure VIII-3 shows curves of pH versus suspended solids for two different types of waste (CSO of 12/9/75 and raw sewage of 3/2/76) tested with two different alum to polyelectrolyte concentration ratios (60:1 and 50:3 respectively). Other test conditions were approximately equivalent. As is expected, when there is relatively more polyelectrolyte present, optimal pH for separation efficiency moves in the basic direction (towards pH 8) while when relatively more alum is present, optimal pH moves in the opposite direction (towards pH 6). Other chemical factors present in the waste may also play a part, but the flocculant concentration ratios seemed to be of primary importance in the tests conducted in this study.

While good flocculation was always achievable without pH adjustment, somewhat better separation might have resulted in many instances by slight pH adjustments. However, the acceptable range of pH for good separation is wide enough to accommodate normal waste water fluctuations making continuous pH monitoring and adjustment unnecessary.

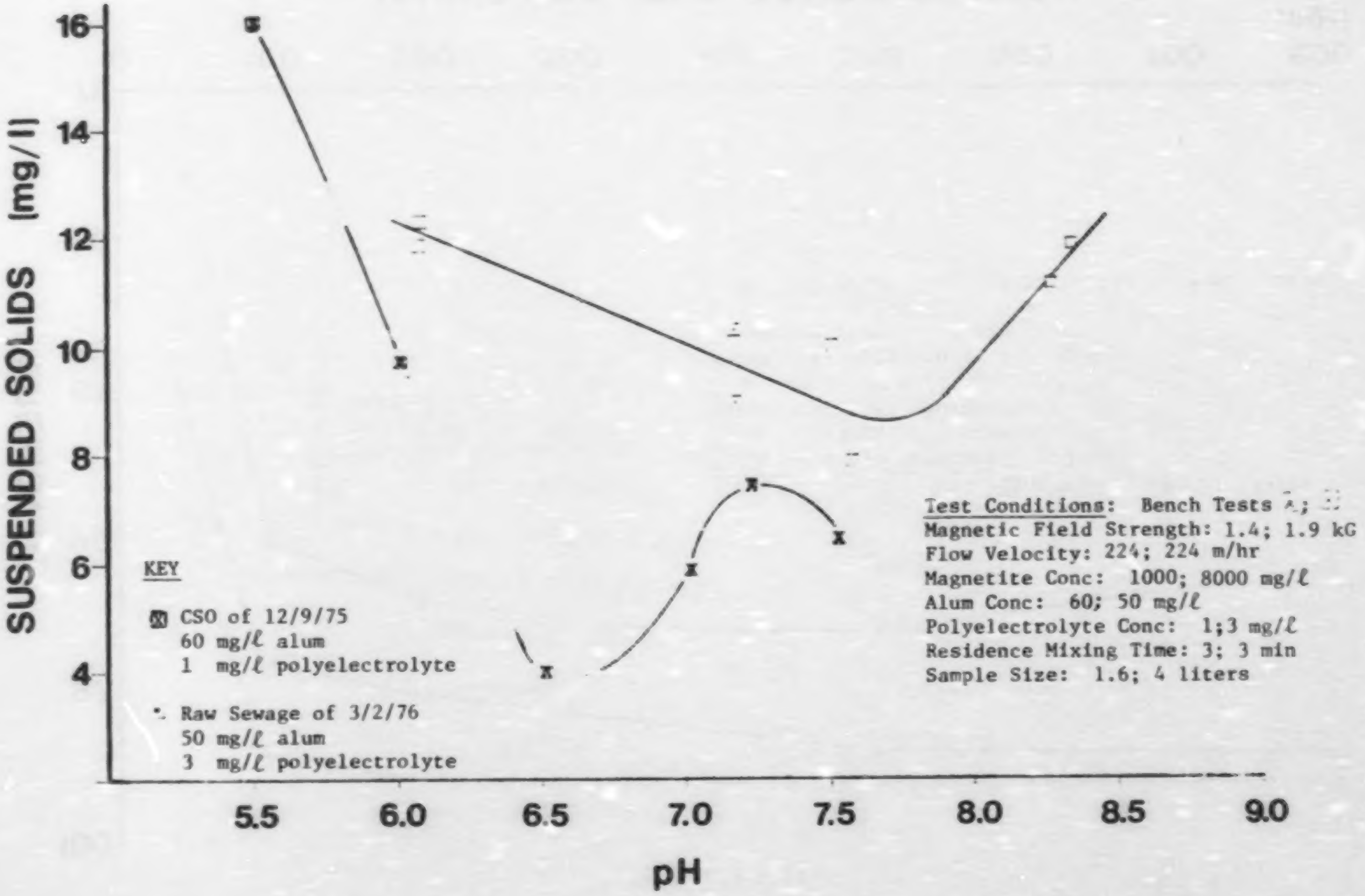
MAGNETIC PARAMETERS AND THEIR INTERACTIONS

Magnetite Seed

Magnetite seed is necessary to impart a magnetic property to the flocculated solids in the water, thus allowing for floc retention inside the magnetized matrix of SALA-HGMS magnetic separators. Figure VIII-4 shows the relationship between magnetite concentration and percent removal of suspended solids, apparent color, and turbidity on a pilot plant run (CSO of 2/2/76). The curve shows that a minimum concentration of magnetite (100 mg/l in this case) is needed for optimal removal. Above this value additional magnetite neither improves nor degrades separation efficiency. For concentrations below 100 mg/l removal percentages decrease rapidly, indicating that insufficient magnetite seed is available as nuclei around which flocs may form.

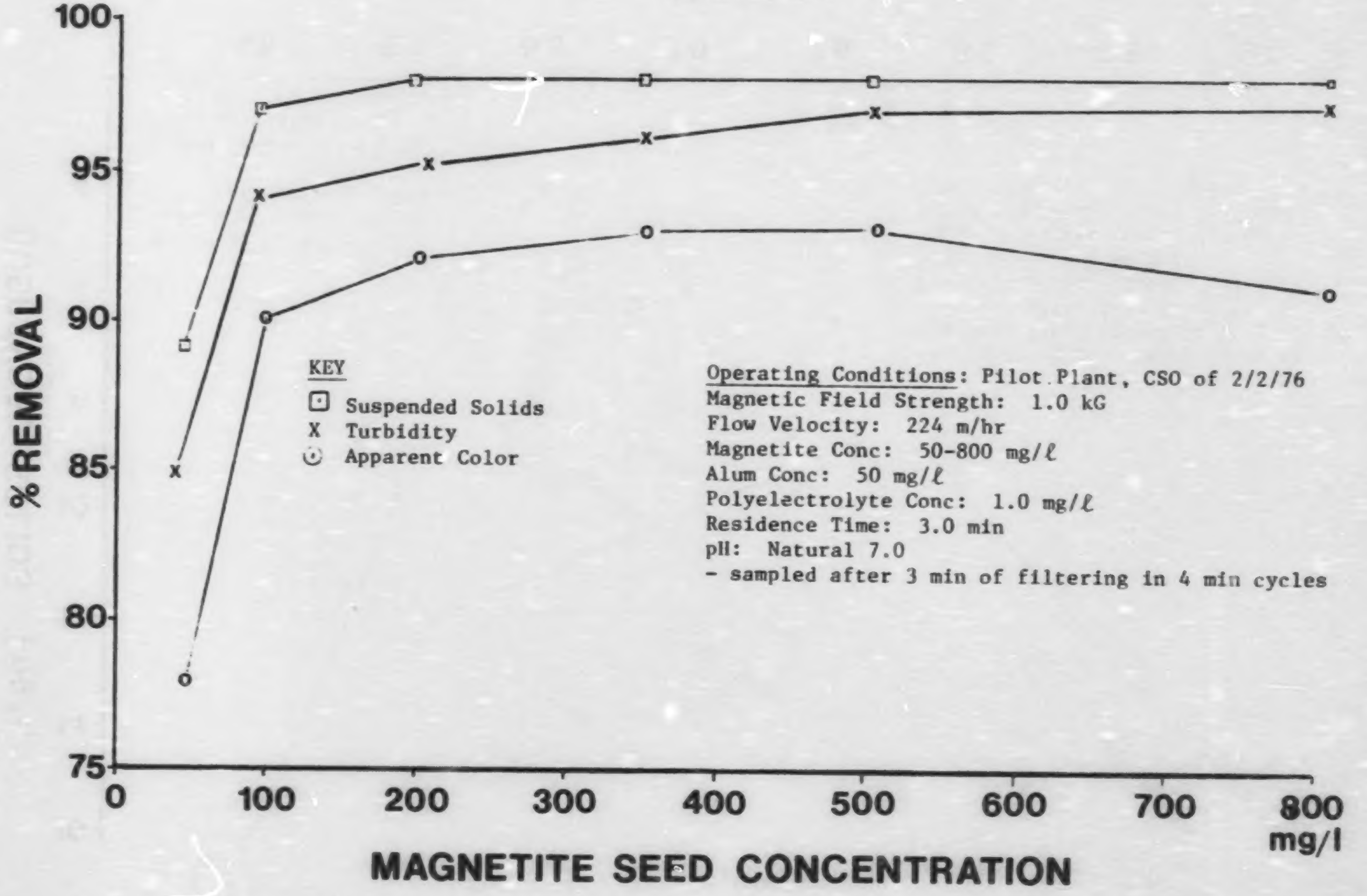
The ratio of magnetite seed to suspended solids is critical for effective separation, since unnucleated flocs will not be trapped in the magnetic filter. The seed to solids ratio for tests in which effective separation took place ranged from 0.38 to 3.05. The insensitivity of the system to magnetite concentration above a certain level is advantageous since the concentration

FIGURE VIII-3



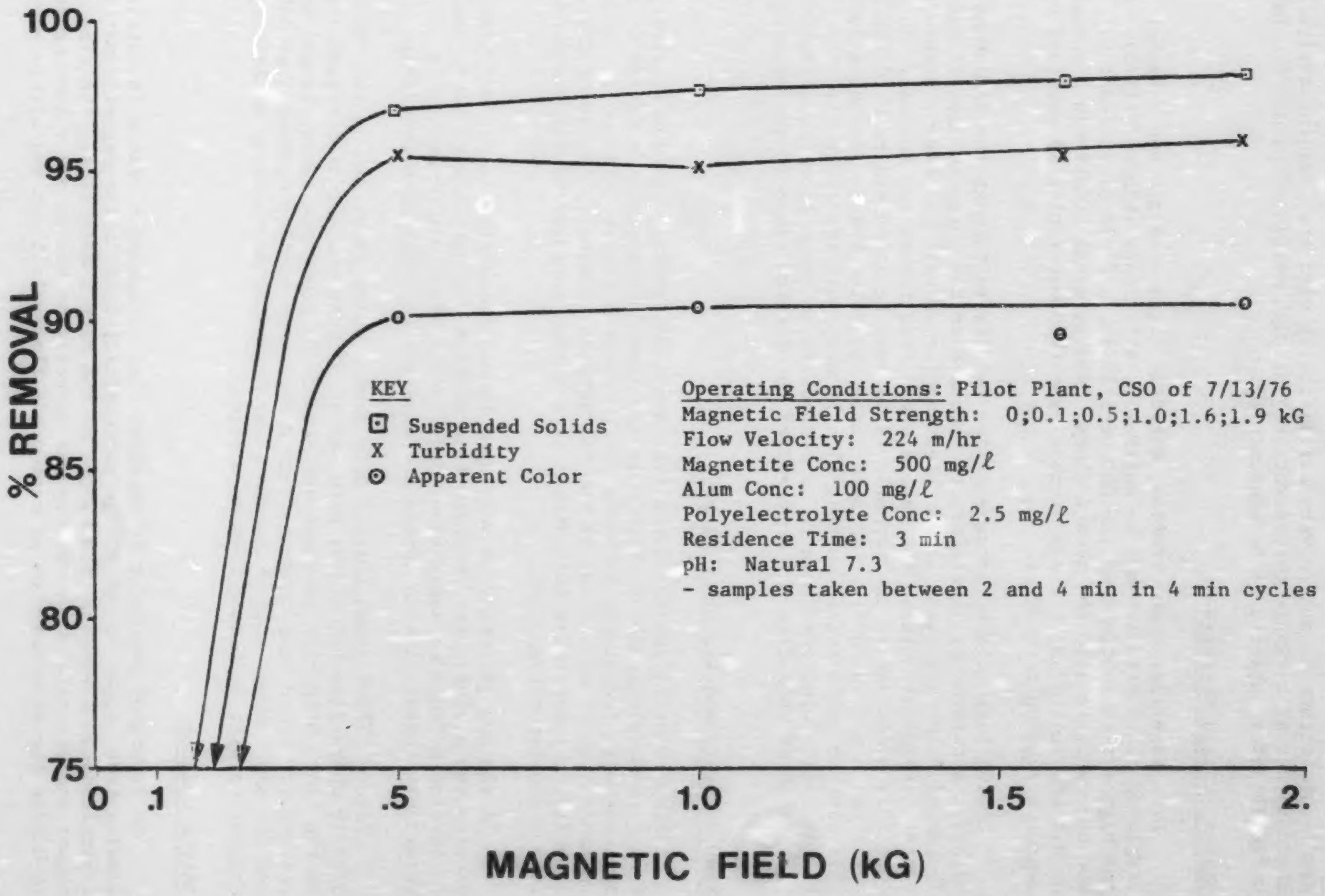
Test Conditions: Bench Tests A; B
Magnetic Field Strength: 1.4; 1.9 kG
Flow Velocity: 224; 224 m/hr
Magnetite Conc: 1000; 8000 mg/ℓ
Alum Conc: 60; 50 mg/ℓ
Polyelectrolyte Conc: 1;3 mg/ℓ
Residence Mixing Time: 3; 3 min
Sample Size: 1.6; 4 liters

FIGURE VIII-4



Operating Conditions: Pilot Plant, CSO of 2/2/76
Magnetic Field Strength: 1.0 kG
Flow Velocity: 224 m/hr
Magnetite Conc: 50-800 mg/ℓ
Alum Conc: 50 mg/ℓ
Polyelectrolyte Conc: 1.0 mg/ℓ
Residence Time: 3.0 min
pH: Natural 7.0
- sampled after 3 min of filtering in 4 min cycles

FIGURE VIII-5



used could either be set to vary automatically with the influent solids or could be set at a single concentration just high enough to handle the highest solids loading expected to be encountered.

Magnetic Field Strength

Like magnetite concentration, magnetic field strength has a rather straightforward relationship to separation efficiency (Figure VIII-5). For the high matrix loadings of the CSO of 3/17/76, a field of at least 0.5 kG was necessary to hold the seeded flocs. Almost total breakthrough occurred at 0.1 kG, indicating the all-or-none type response typically obtained with magnetic seeding techniques.

During surge flows, increased flow velocities through the SALA-HGMS magnetic separator are necessary to accommodate the large volumes of water. Increased flow rate means larger shearing forces will be present within the system, especially within the matrix where drag forces are maximal. To overcome this added stress the magnetic field must be increased to hold the magnetic flocs more securely. In such cases, polyelectrolyte concentration may also have to be increased so that floc breakup will not occur. Seed to solids ratios used also have to be considered in surge flows as a higher proportion of magnetite may be required to hold the flocs in the magnetic matrix.

Flow Velocity and Residence Time

Flow velocity and residence time are also directly related to surge flow. As mentioned above, flow velocity through the magnetic matrix will increase with increasing influent surges (unless reserve systems are adequate to handle the flow). Also, if the flocculation mixing tanks are of fixed capacity, a large surge will result in a faster turnover of water and therefore a shorter mixing time.

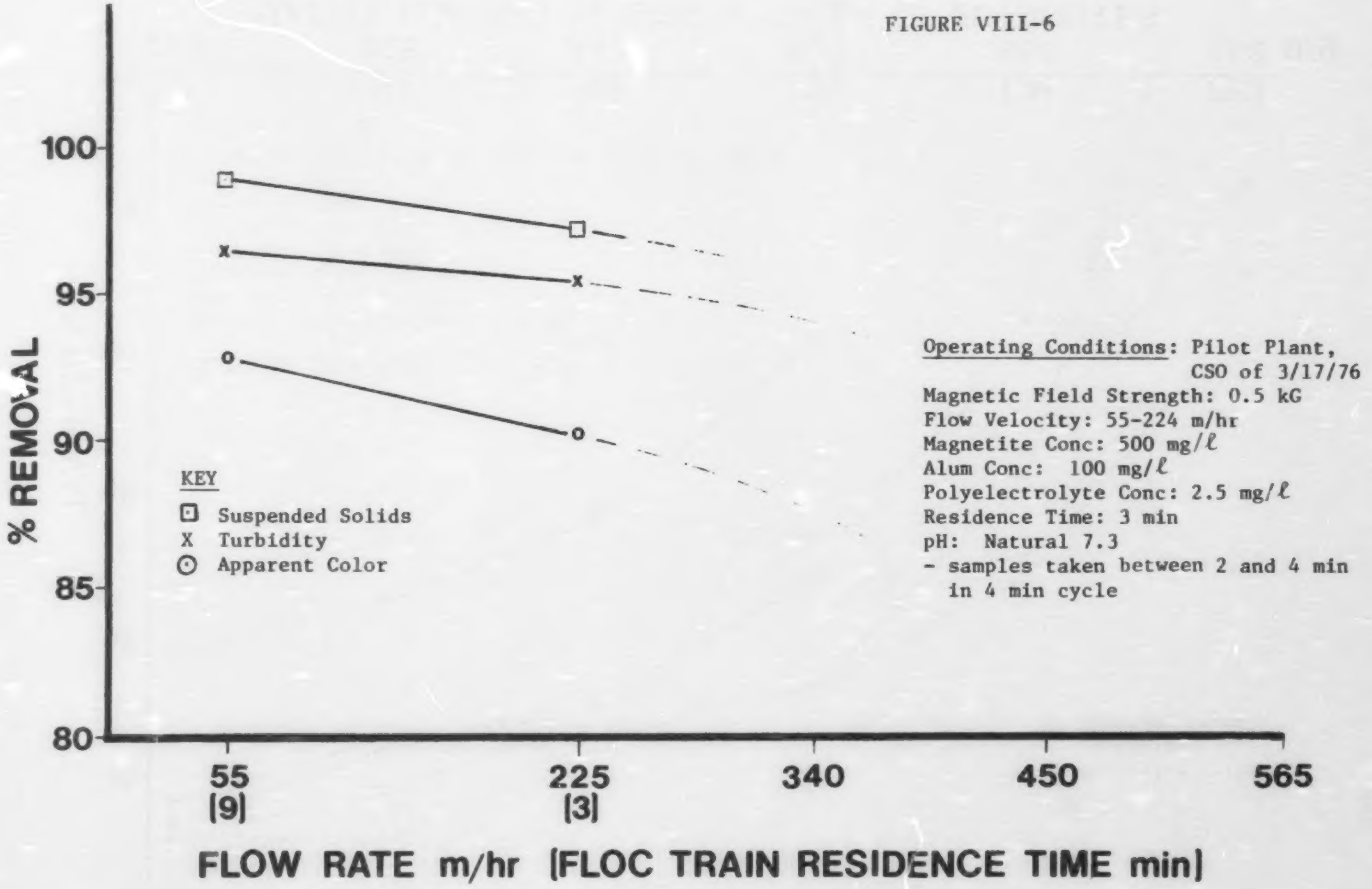
In the present study it was found that a residence time of only three minutes was adequate for complete flocculation. Longer mixing times had no adverse effects on separation efficiency. Thus this parameter is relatively insensitive to change and need not be controlled precisely.

Figure VIII-6 shows limited data from a pilot plant run on the CSO of 3/17/76 where flow velocities were set at 55 m/hr and 222 m/hr respectively. As the floc chain size remained unaltered, the residence times changed accordingly. Bench test runs on other waste water samples performed at 340, 450 and 565 m/hr showed similar trends (i.e. a gradual decrease in efficiency of separation with increased flow velocities).

Matrix Loading

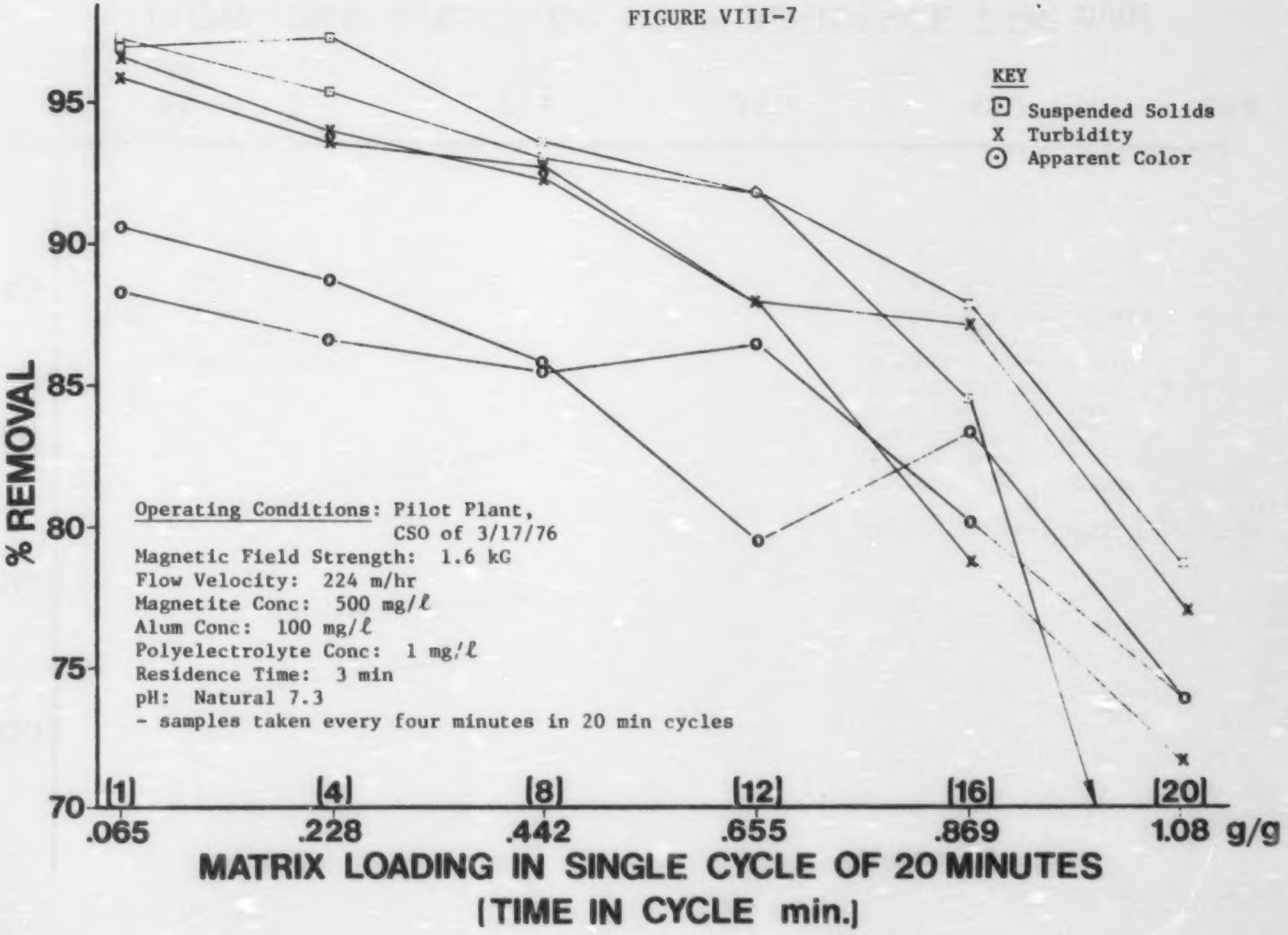
An important parameter to consider when designing a system is matrix loading (the weight of the sludge successfully held in the magnetic matrix in a single cycle divided by the weight of the matrix material). The size of the magnet and the related system depends directly on the matrix volume needed to handle the expected flow at reasonable flow velocities and within adequate

FIGURE VIII-6



Operating Conditions: Pilot Plant,
CSO of 3/17/76
Magnetic Field Strength: 0.5 kG
Flow Velocity: 55-224 m/hr
Magnetite Conc: 500 mg/ℓ
Alum Conc: 100 mg/ℓ
Polyelectrolyte Conc: 2.5 mg/ℓ
Residence Time: 3 min
pH: Natural 7.3
- samples taken between 2 and 4 min
in 4 min cycle

FIGURE VIII-7



Operating Conditions: Pilot Plant,
CSO of 3/17/76
Magnetic Field Strength: 1.6 kG
Flow Velocity: 224 m/hr
Magnetite Conc: 500 mg/ℓ
Alum Conc: 100 mg/ℓ
Polyelectrolyte Conc: 1 mg/ℓ
Residence Time: 3 min
pH: Natural 7.3
- samples taken every four minutes in 20 min cycles

cycle time. Thus that point in a prolonged cycle at which filtration efficiency drops below acceptable levels should be determined before a system is designed.

Figure VIII-7 shows data obtained from continuous pilot plant operation on the CSO of 3/17/76. Two identical continuous twenty-minute cycles were run (with a single flushing interval between) with samples being collected periodically throughout. Once again, the high total solids loading of the feed (including suspended solids, magnetite, alum and polyelectrolyte) should be noted (980 mg/l) as well as the flow rate (4 liters/minute). These figures give a 3.9 g/min input into the magnetic matrix, which itself weighs only about 72 grams. Matrix loading calibrations given on the axis of Figure VIII-7 are corrected values, taking into account the total solids input less the amount which has broken through at the specified time into the cycle.

It is apparent from Figure VIII-7 that rapid breakthrough began to occur somewhere between 12 and 16 minutes into the cycle (at matrix loadings of between 0.65 and 0.87 g solids/g matrix). In a previous continuous pilot plant run (1/29/76, raw sewage) a twelve minute cycle produced a matrix loading of 0.38 g solids/g matrix without any measurable breakthrough. Once again, the relative amount of polyelectrolyte used could make a difference in possible matrix loading, since its chief value is in strengthening the flocs. The 1/29/76 sewage had much lower solids loadings (620 mg/l) to begin with, making the necessary polyelectrolyte concentration used (1 mg/l) relatively higher than that required in the 3/17/76 run.

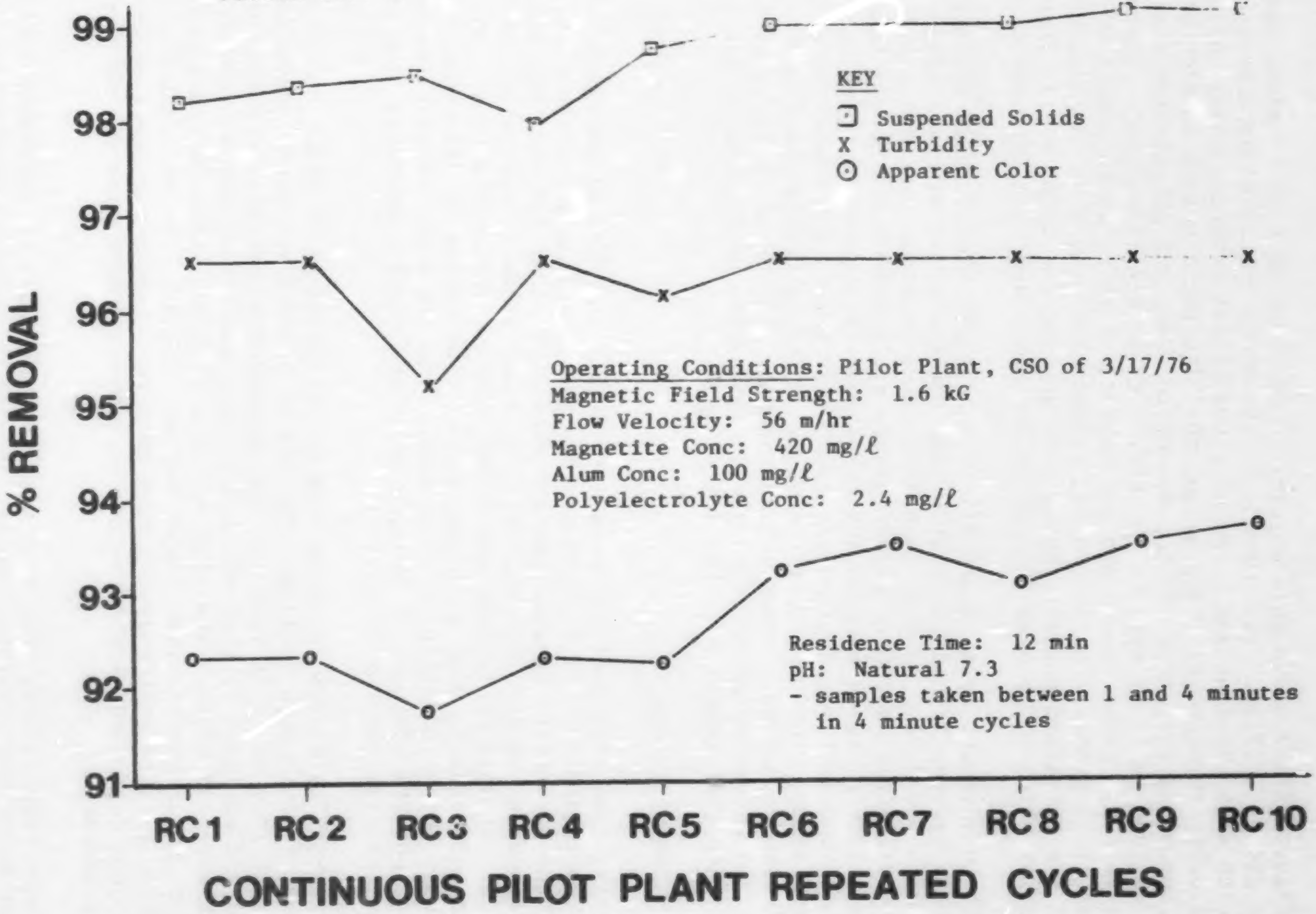
OPTIMAL PARAMETER RUNS

Using data from previous runs as a basis, the optimal parameter settings can be approximated. It is evident from the preceding discussions that almost all of the parameters tested interact with each other and with the influent feed in complex ways. Thus the term "optimum" as used here is an oversimplification. As more is learned about the relative importance of all interactions occurring in such a system, better fine tuning of the process will inevitably become possible. Nevertheless, the presently known parameter interactions are adequate to produce excellent results approximating the true optimum magnetic separation possible.

Figure VIII-8 shows results from an optimized pilot plant run of about one hour of continuous cycling. The CSO of 3/17/76 was used. Data are given in tabular form in Table VIII-1. Ten consecutive four minute cycles were sampled and analyzed to test the consistency and efficiency of separation under these conditions. The only variable that may have changed slightly during this run was the feed input loading. This was because the CSO was drawn from a fifty-gallon drum during this run, and as the level of the water in the drum decreased, higher solids loadings may have been encountered, despite frequent agitation.

These results show that very high removal rates of suspended solids, apparent color and turbidity can be achieved by magnetic separation. Comparison of these data with other figures reported in this study show substantial increases in percent removal for this optimized run. That is attri-

FIGURE VIII-8



Operating Conditions: Pilot Plant, CSO of 3/17/76
Magnetic Field Strength: 1.6 kG
Flow Velocity: 56 m/hr
Magnetite Conc: 420 mg/ℓ
Alum Conc: 100 mg/ℓ
Polyelectrolyte Conc: 2.4 mg/ℓ

Residence Time: 12 min
pH: Natural 7.3
- samples taken between 1 and 4 minutes
  in 4 minute cycles

butable to two factors. The first and most obvious is that optimized conditions naturally give better separation than combined average data derived over a wide range of non-optimum parameter variations. Secondly, it has been found throughout this study that when good separation is being achieved (conditions near optimum) solids in the filtrate (all forms) consistently reach the same general minimum range of concentrations (1-10 mg/l), regardless of the solids loading of the feed. Although it is true that highly polluted feeds cannot have contaminant concentrations reduced to as low levels as lightly polluted feeds, the difference is so small relative to the feed concentrations that they are insignificant. The result of all this is that with heavily laden feeds (like that of 3/17/76), higher percent removals will be obtained than for less polluted waste waters. The same relationship holds true for fecal and total coliform, and all other parameters of water quality tested in this study.

Figure VIII-8 shows that variation in removal efficiency was small, about 1.2% for suspended solids, 1.5% for turbidity, and about 1.8% for apparent color. During this continuous cycling, a slight increase in separation efficiency is noted. This may be due to the changing quality of influent feed or to a gradual stabilization of the system (note the slight drop in percent removal early in the cycle).

Figure VIII-9 shows data from fecal and total coliform analyses on the above optimized run. Feed concentrations are indicated by vertical bars, indicating the variation encountered in the analysis of a single feed sampled during this run. It is of interest to note that while percent removal of suspended solids, apparent color and turbidity are increasing (concentrations are decreasing) with running time (Figure VIII-8), the bacterial concentrations in the filtered samples show a tendency to increase. This discrepancy is difficult to explain. One possibility is that as the system stabilized, a better overall separation was accomplished. At the same time, a stratification of coliform bacterial concentrations in the feed barrel may have caused a biasing of the input coliform concentration with time. In any case, the difference from start to finish is only 0.2 to 0.3% in terms of percent of the total bacteria removed.

Data from this optimized run were also used to plot cumulative probability curves for fecal and total coliform bacteria (Figure B-1) and suspended solids and apparent color (Figure B-2). Because of the limited number of data points the curves provide only approximations. The probability axis (X) gives the percentage of the cycles tested in which values of the parameters plotted (on the Y axis) are expected to be less than the value of Y. Due to the small number of data points used, extrapolation to the outer limits is difficult (especially in Figure B-1 for coliform where substantial measurement variations are inherent with the technique itself).

Table A-11 shows results obtained from CSO analyses for the optimized run of 3/17/76 as well as for the two previous continuous pilot plant runs. High gradient magnetic separation consistently reduced COD an average of 75% in these tests, regardless of the initial chemical oxygen demand present in the CSO or raw sewage.

Table A-12 shows raw data for trace metal analyses for the same three pilot plant runs. It can be seen that magnetic separation was successful in most cases in reducing trace metals to nondetectable or very low levels. On the optimized run of 3/17/76 (labelled RC), a similar improving separation can be seen for both COD and trace metals (confirming the trend noted above for suspended solids, apparent color and turbidity, which is assumed to relate to a gradual stabilization of the flocculation chain operation).

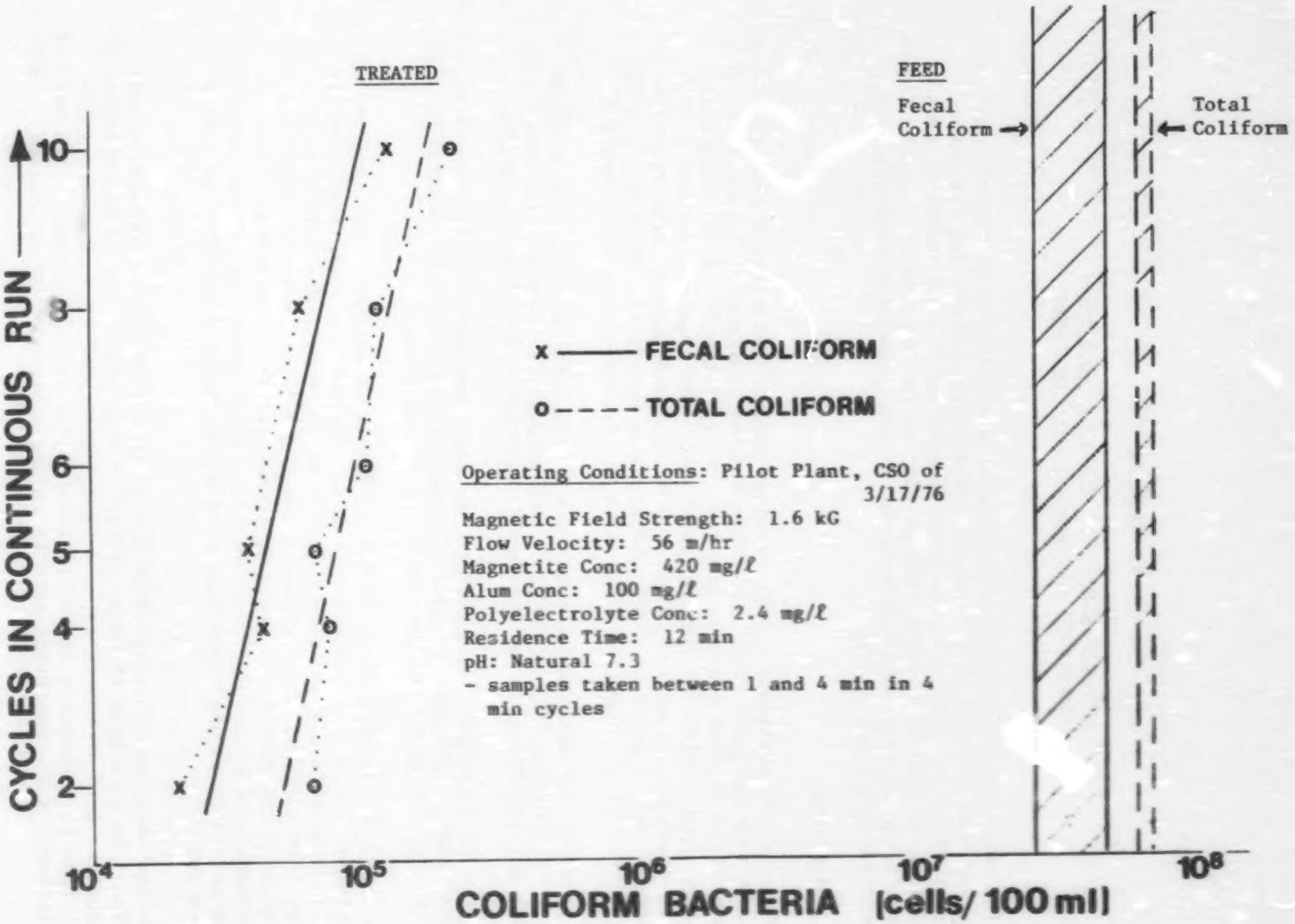


FIGURE VIII-9 COLIFORM BACTERIA IN CONTINUOUS PILOT PLANT RUN

SECTION IX

COMPARISON OF HIGH GRADIENT MAGNETIC SEPARATION TO CONVENTIONAL TREATMENT

The comparison of high gradient magnetic separation to conventional processes has been divided into separate comparisons for CSO and for sewage treatment systems. This has been done because most conventional systems do not perform as well in treating CSO as they do in treating dry weather flows. The wide range in flows and influent characters causes the inadequacy in conventional treatment of CSO.

COST COMPARISONS

For the CSO application high gradient magnetic separation compares favorably with some tertiary level physical-chemical treatments. Table IX-1 below compares costs of high gradient magnetic separation with various alternate processes under evaluation for CSO treatment. The capital cost for a high gradient magnetic separation integrated wet and dry weather flow facility is $107,000/mgd as compared to $168,000/mgd for a comparable physical-chemical facility, and $73,000/mgd for dual media filtration with polyelectrolyte.

Operation and maintenance costs are $0.137/1000 gal. for high gradient magnetic separation, $0.187/1000 gal. for comparable physical-chemical treatment and $0.169/1000 gal. for dual media filtration with polyelectrolyte.

Table IX-2 compares high gradient magnetic separation with several conventional sewage treatment processes. High gradient magnetic separation also compares very favorably for the treatment of raw sewage.

A cost comparison that is rather difficult to estimate, but that should be mentioned, is that of reserve capacity. Systems employing high gradient magnetic separators can increase capacity in two ways. One method is to increase flow velocity while simultaneously increasing magnetic field and the other is to bring additional magnetic separators into operation. Since conventional systems generally do not have this flexibility, these two considerations in particular make high gradient magnetic separation an attractive process.

Sludge handling considerations are another area where accurate comparisons cannot be made with the data presently available. Due to the presence of the magnetite seed in the flocs, the sludge generated is much denser (∿20-30% wt) than that produced in conventional waste water treatment. The mass of the relatively heavy magnetite acts to reduce the sludge water content. Addi-

TABLE IX - 1

COMPARISON OF CSO TREATMENT PROCESSES*

TREATMENT PROCESS	% REMOVAL			CAPITAL COSTS** 25 MGD	OPERATION AND MAINTENANCE** $/1000 gal
	SUSPENDED SOLIDS	TOTAL BOD_5	COLIFORM BACTERIA		
High Gradient Magnetic Separation	92-98	90-98	99-99.99	$ 2,672,600	$ 0.137
Physical Chemical Treatment***	99	94	99	4,190,000	0.187
Dual Media Filtration with Polyelectrolyte	36-92	66-79	--	1,817,000	0.169
Rotating Biological Contactor	70	54	--	862,500	0.053
Contact Stabilization	92	83	83	2,251,100	0.058
High Rate Trickling Filtration	65	65	83	2,275,600	0.073
Dissolved Air Flotation with Fine Screening	56-77	41-57	99	968,300	0.079
Microstrainers	70	50	--	325,500	0.0023

---

* Reference #3

** Since operating costs from "Urban Stormwater Management and Technology: An Assessment" are expressed in 1974, January $, these figures have been adjusted by +20% to effect a fair comparison to high gradient magnetic separation. Capital costs are adjusted to ENR = 2300.

*** Albany, N.Y. Pilot Plant (Ref. 3)

TABLE IX - 2

COMPARISON BETWEEN HIGH GRADIENT MAGNETIC SEPARATION AND OTHER SEWAGE TREATMENT PROCESSES*

	% REMOVAL				OPERATION AND
TREATMENT PROCESS	SUSPENDED SOLIDS	COD	COLIFORM BACTERIA	CAPITAL COSTS** 25 MGD	MAINTENANCE** $/1000 gal
High Gradient Magnetic Separation	88-95	60-75	99-99.9	$ 2,672,600	$ 0.137
Chemical Clarification	60	--	--	1,522,500	--
Activated Sludge Treatment	55-95	70-80	90-98	11,132,000	0.085
Physical Chemical Treatment	99	80	99+	4,190,000	0.187

---

* Fair, G.M., Geyer, J.C. and Okun, D.A., Water Purification and Water Treatment and Disposal, Vol. 2, John Wiley & Sons, New York, 1968, pp. 21-72.

** Since operating costs from "Urban Stormwater Management and Technology: An Assessment" are expressed in 1974, January $, these figures have been adjusted by +20% to effect a fair comparison to high gradient magnetic separation. Capital costs are adjusted to ENR = 2300.

tional cost savings may be realized from reduced thickener and dewatering equipment size and better landfill properties.

COMPARISON OF REMOVAL PERFORMANCE

The removal performance of high gradient magnetic separation is excellent in comparison with other processes. Tables IX-1 and IX-2 compare high gradient magnetic separation to some conventional treatment systems.

The removal performance of high gradient magnetic separation exceeds that of all but physical-chemical treatment. High gradient magnetic separation, in a single stage treatment not only attains removal efficiencies exceeding those of conventional treatment, but in addition, significantly reduces the levels of phosphate(15), heavy metal (Table A-13) and viral contamination(2) in waste waters.

APPLICATION TO EFFLUENT POLISHING

High gradient magnetic separation can be utilized as a very good effluent polishing step. Tests conducted on CSO indicate that suspended solids levels of < 30 mg/l can be successfully reduced to very low levels, even < 2 mg/l. Heavy metal, viral, and phosphorus contamination can also be reduced to low levels using this process. Capital and operation and maintenance costs should also be considerably lower than conventional systems for this application because pretreatment and sludge dewatering systems would not be included in the high gradient magnetic separator system.

SECTION X

COST ESTIMATES FOR HIGH GRADIENT MAGNETIC SEPARATION TREATMENT

Estimated capital, operating and maintenance costs have been projected from the data obtained in this study. The excellent removal efficiencies obtained in the treatment of both CSO and raw sewage have indicated that high gradient magnetic separation treatment would be best utilized for integrated wet and dry weather flow systems. A schematic flow sheet for the 25 mgd facility is shown in Figure X-1.

Table X-1 below gives estimated capital costs for this system broken down into subsystems. The cost estimate includes process control equipment for an entirely automatic system. Costs for effluent quality analyzers are also included.

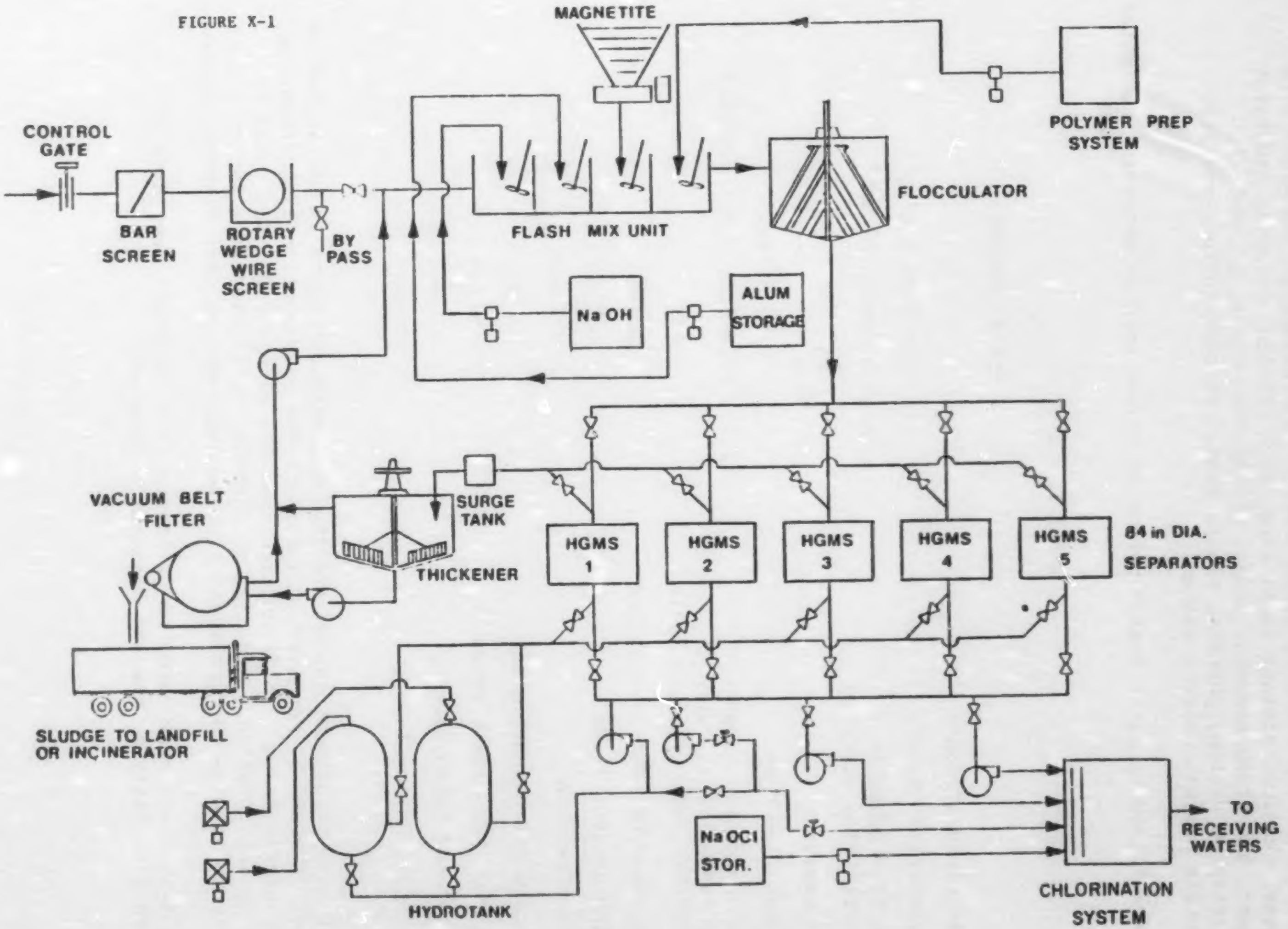
TABLE X - 1

25 MGD INTEGRATED WET AND DRY WEATHER FLOW TREATMENT FACILITY*

System	Capital Cost
Pre-Screening	$ 132,000
Floc Train and Chemical Feeding and Storage	293,900
Thickening and Dewatering Equipment	218,250
Backflush System	169,500
High Gradient Magnetic Separators (5 @ $165,600 ea.)	828,000
Pumps, Filter	47,300
Chlorination System	42,250
Process Control	108,000
Miscellaneous	30,000
Physical Plant	110,000
Installation Costs not Included in Above	229,600
	$2,208,800
Construction Contingency 10%	220,800
	$2,429,600
Engineering and Administration 10%	243,000
Total Capital Cost	$2,672,600

*ENR = 2300

FIGURE X-1



CONTROL GATE
BAR SCREEN
ROTARY WEDGE WIRE SCREEN
BY PASS
MAGNETITE
FLASH MIX UNIT
FLOCCULATOR
POLYMER PREP SYSTEM
Na OH
ALUM STORAGE
VACUUM BELT FILTER
SURGE TANK
THICKENER
HGMS 1
HGMS 2
HGMS 3
HGMS 4
HGMS 5
84 in DIA. SEPARATORS
SLUDGE TO LANDFILL OR INCINERATOR
HYDROTANK
Na OCl STOR.
CHLORINATION SYSTEM
TO RECEIVING WATERS

25 MGD SALA-HGMS INTEGRATED WET AND DRY WEATHER COMBINED SEWER TREATMENT FACILITY

Capital Costs Include: control gate, coarse bar screen, grit chambers, rotary wedge wire screens, flash mixers, flocculators, flocculant feed systems, chemical storage facilities, high gradient magnetic separator systems, backflush systems, pumps, piping, conveyors, pH control, chlorination system, physical plant, land, instrumentation, and programmable process control system.

Table X-2 following lists design parameter values used in obtaining estimated costs.

TABLE X - 2

	Design Values
Magnetic field strength	1.5 kG
Flow velocity in matrix	245 m/hr (100 gpm/ft^2)
Maximum flow capacity @ 100 gpm/ft^2 flow velocity	1.18 m^3/sec (25 mgd)
Nominal capacity	0.60 m^3/sec (12.5 mgd)
Back flush flow rate	0.95 m^3/sec
Flow rate/magnetic separator @ maximum capacity, 100 gpm/ft^2 flow velocity, and 90% duty cycle	12.7 m^3/min (3.4 x 10^3 gal/min)
Average influent suspended solids	300 mg/1
Magnetite concentration	300 mg/1
Alum concentration	100 mg/1
Polyelectrolyte concentration	1.0 mg/1
Pumping head for filter pumps	7.6 m (25 ft)
"G" factor for flash mixer	300/sec
"G" factor for flocculators	100/sec

Costs of a pH adjustment system are included although there is little indication that it would be required. Also costs for a conventional chlorination facility are included. It is assumed that the sludge generated would be shipped to incineration, landfill, or disposal facilities at a larger plant. Evaluation of sludge characteristics would indicate the best disposal means.

Installation costs were based on estimates from equipment suppliers and estimates from Perry's Chemical Engineer's Handbook.

OPERATION AND MAINTENANCE

Operation and maintenance costs are based on operating conditions as listed in Table X-2. The maintenance costs are based on annual operation at 50% capacity. Chemical costs are not included for pH control as pH adjustment was not necessary for any tests conducted in this study. Similarly, the operating costs for the final chlorination step were not included due to lack of data on the chlorine demand of the effluent. Table X-3 below gives operation and maintenance costs expected for a 25 mgd integrated wet and dry weather flow treatment facility based on annual operation at 50% of maximum system capacity.

The operator labor is given for 24 hr/day monitoring of the facility. In addition an 8 hour shift is included for routine labor in the facility (i.e., lubrication, cleaning bar and screening equipment). The operator labor figure may be too conservative as the plant is designed for automatic operation.

An evaluation of the sludge handling costs is difficult due to the many considerations necessary. These conditions are economic, ecological and legal (referring to laws pertaining to disposal methods) in nature.

For many applications, especially those involving low solids loading, the magnetite seed costs are small compared to other processing costs and thus a recycle step may not be economically justified. Ecological considerations such as improved land filling qualities resulting from a very dense sludge may also favor the seed discard option. On the other hand, seed recycle might be advantageous for some large scale, continuous flow (dry weather flow) treatment facilities. The economies of scale therein might justify the additional capital expenditures in order to minimize such operational costs. Determination of representative characteristics for sludges generated by seeded high gradient magnetic separation treatment will indicate which option is most applicable to the specific case.

The electrical cost breakdown (Table X-4) shows that the power consumption by the electromagnetic coils in the SALA-HGMS magnetic separators is relatively small in comparison to power requirements of the other process equipment. For operation at 1.5 kG mangetic field the magnetic separators consume only 16% of the total power required.

LAND REQUIREMENTS

Approximate land area required for the above described facility would be 0.35 acres (0.14 hectares). Thus magnetic separation has the additional economic and ecological advantages of consuming only a relatively small amount of land. This is of course much more relevant in highly populated areas where land costs may add significantly to capital investment or in areas where large amounts of land simply are not available.

TABLE X - 3

OPERATION AND MAINTENANCE COSTS

Chemicals	$/1000 gal	$/yr (at 12.5 mgd)
Alum @ $0.132/kg 100 mg/l	0.050	$ 228,000
Magnetite @ $0.022/kg 300 mg/l (does not include freight charges)	0.025	114,000
Polyelectrolyte @ $3.10/kg	0.012	55,000
Total Chemical Costs	0.087	$ 397,000
Operator Labor		
32 Manhours/day @ $10/hr	0.026	119,000
Maintenance		
Mechanical Equipment and physical plant (3% of equipment costs)	0.012	55,000
Electrical, Instrumentation and Piping (2% of equipment costs)	0.002	9,000
Total Labor and Maintenance	0.040	$ 183,000
Electrical		
@ $0.020/kWh SALA-HGMS magnetic separators @ 1.5 kG require 85 kWh; other equipment 440 kWh	0.010	46,000
Total Operations and Maintenance Costs	0.137	$ 626,000

TABLE X - 4

POWER CONSUMPTION

SALA-HGMS Magnetic Separators @ 1.5 kG	85 kWh
Flash Mixer Units (3)	135
Flocculators	52
Air Compressor @ 70% duty cycle	35
Vacuum Station	48
Filter Pump	130
Miscellaneous Consumption	40
Total	525 kWh

SALA-HGMS magnetic separators use approximately 16% of total power consumption

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APPENDIX A

TABLES OF SUMMARIZED DATA

TABLE A-1. BENCH TEST*

CSO COLLECTED ON 12/9/75	SUSPENDED SOLIDS (mg/1)	APPARENT COLOR (PCU)	TURBIDITY (FTU)	COLIFORM TOTAL @ 37°C on EMB AGAR (cells/100 ml)
CONTROL AVERAGE	40.1	224	76.5	4.8×10^8
(Untreated CSO)				
(# of Tests)	(6)	(6)	(6)	(2)
Range (Initial to final)	31.3 - 62.1	185-273	63 - 95	$1.6 \times 10^8 - 8.0 \times 10^8$
TREATED CSO				
Average	2.75	31.2	5.65	7.4×10^6
(# of Tests)	(44)	(46)	(46)	(4)
Range	0.8 - 7.9	18 - 55	2 - 12	$1.4 \times 10^5 - 1.3 \times 10^7$
% REDUCTIONS				
Average	93%	87%	93%	98%
Range	83 - 97%	78 - 92%	86 - 97%	97 - 99.97%

TEST CONDITIONS

Magnetic Field	0.5 - 1.9 kG
Flow Velocity	49.2 - 390 m/hr
Alum Conc.	20 - 200 mg/1
Polyelectrolyte Conc.	0.25 - 1.5 mg/1
Magnetite Conc.	50 - 500 mg/1
pH	4.5 - 7.5
Residence Time	1 - 10 min
Sample Size	1.6 liters

*Combined results of 7 series of tests done over a period of 7 days.

TABLE A-2. BENCH TEST

CSO COLLECTED ON 12/19/75	SUSPENDED SOLIDS (mg/1)	APPARENT COLOR (PCU)	TURBIDITY (FTU)
CONTROL AVERAGE	209	405	145
(Untreated CSO)			
TREATED CSO			
Average	16.7	62	13
(# of Tests)	(3)	(3)	(3)
Range	7.8 - 23.9	52 - 68	10 - 17
% REDUCTIONS			
Average	92%	85%	91%
Range	89 - 96%	83 - 87%	88 - 94%

TEST CONDITIONS

Magnetic Field	1.9 kG	
Flow Velocity	210 m/hr	Magnetite Concentration Varied
Alum Conc.	50 mg/1	
Polyelectrolyte Conc.	1 mg/1	
Magnetite Conc.	250; 500; 1000 mg/1	
pH	Natural	
Residence Time	3 min	
Sample Size	10 liters	
Matrix Loading	0.16 g/g matrix	

TABLE A-3. BENCH TEST

RAW SEWAGE COLLECTED ON 12/26/75	SUSPENDED SOLIDS (mg/1)	APPARENT COLOR (PCU)	TURBIDITY (FTU)
CONTROL AVERAGE	42	480	48
(Untreated CSO)			
TREATED CSO			
Average	9.3	48	12
(# of Tests)	(3)	(2)	(2)
Range	4.0 - 12.6	27 - 68	5 - 18
% REDUCTIONS			
Average	78%	90%	75%
Range	70 - 90%	86 - 94%	63 - 90%

TEST CONDITIONS		Magnetite Concentration Varied
Magnetic Field	1.9 kG	
Flow Velocity	210 m/hr	
Alum Conc.	150 mg/1	
Polyelectrolyte Conc.	2.4 mg/1	
Magnetite Conc.	500 - 750 mg/1	
pH	Natural 7.2	
Residence Time	∿3 min	
Sample Size	10 liters	

TABLE A-4. BENCH STUDY

CSO COLLECTED 12/31/75	SUSPENDED SOLIDS (mg/1)	APPARENT COLOR (PCU)	TURBIDITY (FTU)	FECAL COLIFORM (cells/100 ml)
CONTROL AVERAGE	540	960	430	2×10^8
(Untreated CSO)				
TREATED CSO				
Average	8	30	6	7×10^5
(# of Tests)	(10)	(6)	(6)	(1)
Range	2.0 - 34	17 - 43	3 - 10	----
% REDUCTIONS				
Average	98%	97%	99%	99.7%
Range	94 - 99%	96 - 98%	98 - 99%	----

TEST CONDITIONS

Magnetic Field: 1.0 kG
Flow Flux Rate 210 - 530 m/hr
Alum Conc.: 100 mg/1
Polyelectrolyte Conc.: 1.0 mg/1

pH: natural 7.0
Residence Time: 3 min
Sample Size: 10 liters
Matrix Loading: 0.1 - 0.2 g/g matrix

Flow Velocity, Magnetite Conc., and Matrix Loading varied

TABLE A-5. BENCH STUDY

CSO COLLECTED ON 1/28/76	SUSPENDED SOLIDS (mg/1)	APPARENT COLOR (PCU)	TURBIDITY (FTU)
CONTROL AVERAGE	90	220	70
(Untreated CSO)			
TREATED CSO			
Average	10	79	14
(# of Tests)	(9)	(9)	(9)
Range	6 - 15	62 - 100	8 - 18
% REDUCTIONS			
Average	89%	64%	80%
Range	83 - 94%	55 - 72%	74 - 88%

TEST CONDITIONS

Magnetic Field:	1 kG (permanent magnet)	Magnetite Conc.:	250; 500; 1000 mg/1
Flow Velocity	210 m/hr	pH:	natural
Alum Conc.:	25; 50; 75 mg/1	Residence Time:	5 min
Polyelectrolyte Conc.:	1; 2; 3 mg/1	Sample Size:	4 liters
Matrix Length:	3 inches		

Alum, Polyelectrolyte and Magnetite Conc. varied

TABLE A-6. CONTINUOUS PILOT PLANT
(2 Hour Run)

RAW SEWAGE COLLECTED ON 1/29/76	SUSPENDED SOLIDS (mg/1)	APPARENT COLOR (PCU)	TURBIDITY (FTU)
CONTROL AVERAGE	115	330	110
(Untreated)			
TREATED			
Average	10	65	13
(# of Tests)	(21)	(21)	(21)
Range	7.8 - 11.5	51 - 84	10 - 21
% REDUCTIONS			
Average	91%	80%	88%
Range	90 - 93%	74 - 84%	81 - 91%

TEST CONDITIONS

Magnetic Field: 1.4 kG
Flow Velocity 210 m/hr
Alum Conc.: 50 mg/1
Polyelectrolyte Conc.: 1,2,3 mg/1

Magnetite Conc.: 500 mg/1
pH: natural 7.6
Residence Time : 3 min

Polyelectrolyte Varied

TABLE A-7. CONTINUOUS PILOT PLANT
(2½ Hour Run)

CSO COLLECTED ON 2/2/76	SUSPENDED SOLIDS (mg/1)	APPARENT COLOR (PCU)	TURBIDITY (FTU)	FECAL COLIFORM (cells/100 ml)
CONTROL AVERAGE	260	400	150	2.0×10^6
(Untreated CSO)				
TREATED CSO				
Average	6	38	6	1.0×10^5
(# of Tests)	(10)	(10)	(10)	(1)
Range	3.6 - 8.7	26 -45	4 - 7	----
% REDUCTIONS				
Average	98%	92%	96%	95%
Range	97-99%	89-93%	95-97%	----

TEST CONDITIONS

Magnetic Field: 1.4 kG
Flow Velocity 210 m/hr
Alum Conc.: 50 mg/1
Polyelectrolyte Conc.: 1 mg/1

Magnetite Conc.: 100;200;350;500;800 mg/1
pH: natural 7.0
Residence Time: 3 min

Magnetite Conc. Varied

TABLE A-8. BENCH TESTS

RAW SEWAGE COLLECTED on 3/8/76	SUSPENDED SOLIDS (mg/1)	APPARENT COLOR (PCU)	TURBIDITY (FTU)	FECAL COLIFORM (cells/100 ml)
CONTROL AVERAGE	147	130 - 140	105	1.4×10^7
(Raw Sewage)				
TREATED SEWAGE				
Average	8.4	53	8	8.9×10^4
(# of Tests)	(6)	(7)	(7)	(7)
Range	4.9 - 15.6	41 - 71	6 - 12	$5.6 - 18 \times 10^4$
% REDUCTIONS				
Average	94.3%	83.6%	92.5%	99.4%
Range	89 - 97%	78 - 87%	89 - 94%	98.7 - 99.6%

TEST CONDITIONS

Magnetic Field: 1.95 kG
Flow Velocity: 56 m/hr
Alum Conc: 100 mg/1
Polyelectrolyte Conc: 0; 1.8; 4; 5

Magnetite Conc: 500 mg/1
pH: 5.5; 6.0; 6.5; 7.1; 8.0
Residence Time: 10 min
Sample Size: 4 liters

TABLE A-9. CONTINUOUS PILOT PLANT
(6 HOUR RUN)

CSO COLLECTED ON 3/17/76	SUSPENDED SOLIDS (mg/1)	APPARENT COLOR (PCU)	TURBIDITY (FTU)	FECAL COLIFORM (cells/100 ml)	TOTAL COLIFORM (cells/100 ml)	BOD_5 (mg/1)
FEED AVERAGE	460	650	230	3.6×10^7	6.3×10^7	>79
(# of Tests)	(3)	(3)	(3)	(4)	(4)	(2)
Range	400 - 520	600 - 800	200 - 250	$2 - 5 \times 10^7$	$5.1 - 7 \times 10^7$	>75 - 83
TREATED CSO						
Average	28	85	19	5.3×10^4	1.1×10^5	6.0
(# of Tests)	(42)	(42)	(42)	(6)	(6)	(4)
Range	4.1 - 185	41 - 210	8 - 65	$1.5 - 13 \times 10^4$	$0.70 - 2.2 \times 10^5$	5.2 - 7.0
% REDUCTIONS						
Average	94%	87%	92%	99.85%	99.83%	>92%
Range	60 - 99%	68 - 94%	72 - 97%	99.64-99.96%	99.65-99.88%	>91-93%

TEST CONDITIONS

Magnetic Field: 0.1; 0.5; 1.0; 1.9 kG
Flow Velocity: 56; 225 m/hr
Alum Conc.: 50; 70; 100; 150; 200 mg/1
Polyelectrolyte Conc.: 0; 0.1; 0.5; 1; 2; 2.5 mg/1

Magnetite Conc.: 200; 420; 500 mg/1
pH: Natural 7.3
Residence Time: 3; 12 minutes

TABLE A-10. CONTINUOUS PILOT PLANT: OPTIMIZED RUN

CSO COLLECTED ON 3/17/76	SUSPENDED SOLIDS (mg/1)	APPARENT COLOR (PCU)	TURBIDITY (FTU)	FECAL COLIFORM (cells/100 ml)	TOTAL COLIFORM (cells/100 ml)	BOD_5* (mg/1)
FEED AVERAGE	460	650	230	3.6×10^7	6.3×10^7	>79
(1 sample only)						
(# of Tests)	(3)	(3)	(3)	(4)	(4)	(2)
Range	400 - 520	600 - 800	200 - 250	$2.0\text{-}5.0 \times 10^7$	$5.1\text{-}7.0 \times 10^7$	>75-83
TREATED SAMPLES						
(Continuous Run)						
Average	6.0	47	8	5.3×10^4	1.1×10^5	6.0
(# of Tests)	(9)	(10)	(10)	(6)	(6)	(4)
Range	4.1 - 9.1	41 - 53	8 - 11	$1.5\text{-}13 \times 10^4$	$0.70\text{-}2.2 \times 10^5$	5.2-7.0
% REMOVAL						
Average	98.7%	92.8%	96.3%	99.85%	99.83%	>92%
Range	98.0-99.1%	91.8-93.7%	95.2-96.5%	99.64-99.96%	99.65-99.88%	>91-93%

TEST CONDITIONS

Magnetic Field: 1.6 kG
Flow Velocity: 56 m/hr
Alum Conc.: 100 mg/1
Polyelectrolyte Conc.: 2.4 mg/1

Magnetite Conc.: 420 mg/1
pH: 7.3
Residence Time: 10 min
Cycle Length: 4 min

Samples collected between 1 and 4 minutes into cycle/Continuous stabilized Cycling of 50 minutes. *Feed BOD_5 shown is not accurate as inadequate dilution (1:9) was used. Value is only a minimum BOD_5 possible. The actual undertermined value is expected to be much higher. Likewise the % removal figures are underestimates.

TABLE A-11. COD ANALYSES
(mg/1)

RAW SEWAGE OF 1/29/76*	UNFILTERED	FILTERED
Feed	76	30
Treated (B-3)	25	26
% Reduction	67%	---
CSO OF 2/2/76*		
Feed	137	35
Treated (MA3)	35	32
Treated (MB1)	26	33
Average % Reduction	78%	---
CSO OF 3/17/76 **		
Feed 1	425	
Feed 2	395	
Treated (RC-6)	138	
Treated (RC-7)	101	
Treated (RC-8)	105	
Treated (RC-9)	93.9	
Treated (RC-10)	92.7	
Average % Reduction	74%	

---

* Analyses done by Process Research, Inc., Cambridge, Massachusetts

** Analyses done by Arnold Green Testing Laboratories, Inc., Natick, Massachusetts

TABLE A-12. TRACE METAL ANALYSES (mg/1)

		Cd	Pb	Cr	Hg	Zn	Cu	Ni
RAW SEWAGE OF 1/29/76*								
Feed		< 0.05	< 0.5	< 0.1	0.0011	0.50	0.20	0.3
Treated (B-1)		< 0.05	< 0.5	< 0.1	0.0005	0.11	0.10	0.1
% Reduction		--	--	--	55%	78%	50%	67%
CSO OF 2/2/76*								
Feed		< 0.05	< 0.5	< 0.1	0.0006	0.24	0.15	0.3
Treated (MA-2)		< 0.05	< 0.5	< 0.1	0.0007	0.11	0.05	0.3
% Reduction		--	--	--	0%	54%	67%	0%
CSO OF 2/2/76**								
Feed		< 0.05	0.15	0.02	--	0.20	--	--
Treated (MA-1)		< 0.05	< 0.05	< 0.01	--	< 0.05	--	--
% Reduction		--	> 67%	> 50%	--	> 75%	--	--
CSO OF 3/17/76*								
Feed		.05	.2	.2	.0060	.71	.66	.2
Treated {Optimized Runs}	(RC-3)	< .02	< .2	< .1	.0016	.08	.35	< .2
	(RC-7)	< .02	< .2	< .1	Contam.	.04	.31	< .2
	(RC-9)	< .02	< .2	< .1	.0008	.04	.27	< .2
	(RC-10)	< .02	< .2	< .1	.0006	.04	.27	< .2
{0.5 kG}	(SS-2B)	< .02	< .2	< .1	< .0005	.10	.35	< .2
{1.0 kG}	(SS-2A)	< .02	< .2	< .1	.0012	.08	.35	< .2
{1.6 kG}	(A3-B)	< .02	< .2	.1	Contam.	.10	.35	< .2
{1.9 kG}	(SS-2C)	< .02	< .2	< .1	< .0005	(.43)	.35	< .2
Average % Reductions		> 60%	> 0%	> 50%	> 86%	90%	51%	--

("<" indicates undetectable concentrations present)

* Analyses done by EPA Analytical Applications Laboratory and Cincinnati Water Research Laboratory, Cincinnati, Ohio

**Analyses done by Process Research, Inc., Cambridge, MA

TABLE A-13. COMPARISON OF ALL PILOT PLANT AND BENCH RESULTS

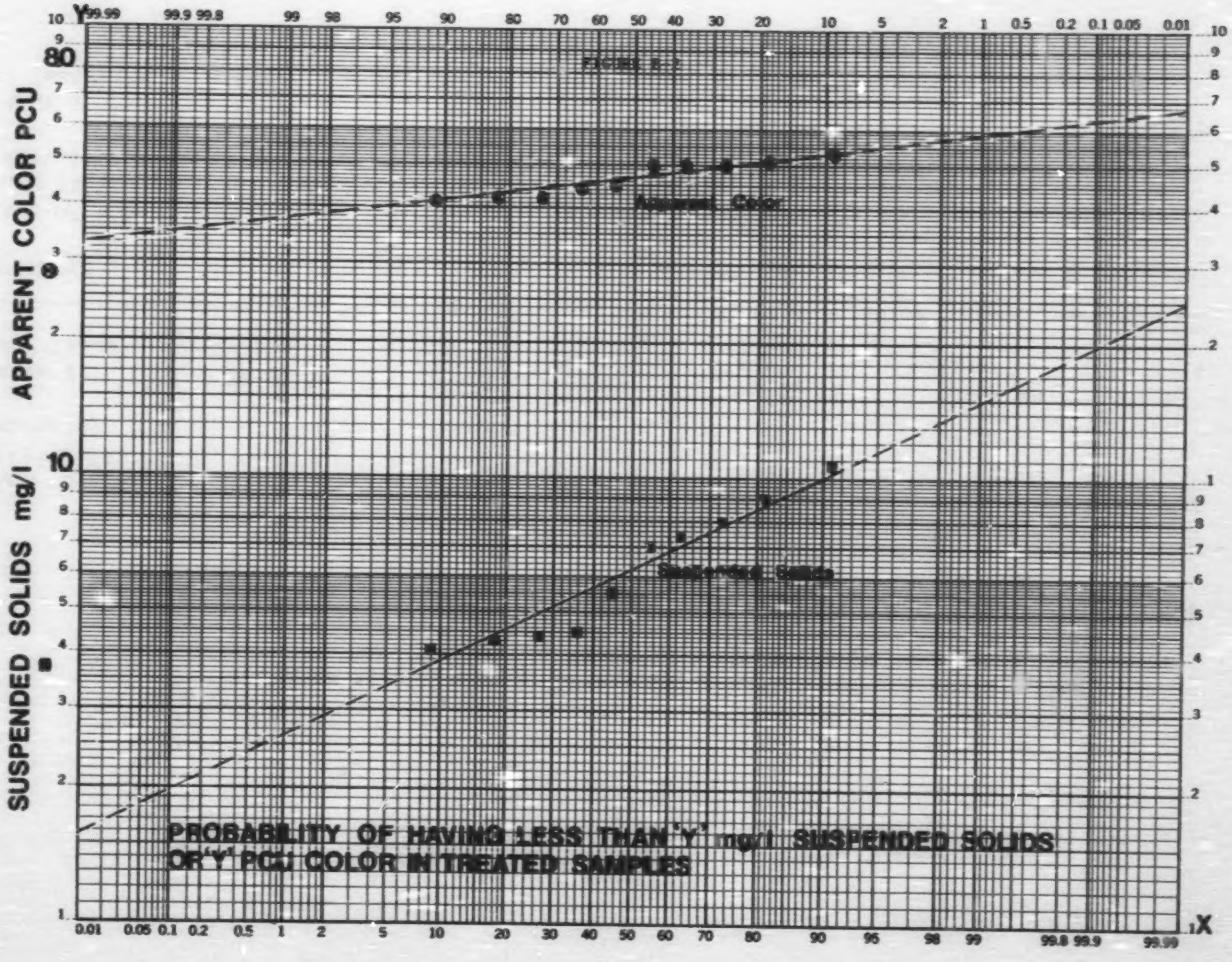
	SUSPENDED SOLIDS	APPARENT COLOR	TURBIDITY	FECAL COLIFORM	TOTAL COLIFORM
PILOT PLANT					
% Removals					
Average	93.7	85.7	91.4	99.85	99.83
(# of tests)	(73)	(73)	(73)	(7)	(6)
Range	60-99	68-94	72-97	99.64-99.96	99.65-99.88
BENCH TESTS					
% Removals					
Average	92.7	84.7	91.3	99.4	98
(# of tests)	(75)	(73)	(73)	(8)	(4)
Range	70-98	55-98	63-99	98.7-99.7	97.99.97

TABLE A-14. SUMMARY OF PERCENT REMOVALS FOR ALL TESTS (BENCH AND PILOT PLANT)

	SUSPENDED SOLIDS	APPARENT COLOR	TURBIDITY	FECAL COLIFORM	TOTAL COLIFORM	BOD_5
CSO						
AVERAGE OF ALL SAMPLES TESTED (% removals)	95	87	93	99.2	99.3	>92
Range % (#of Tests)	83-99.1 (85)	55-98 (78)	74-99 (77)	95-99.96 (8)	97-99.89 (10)	>91-93 (4)
RAW SEWAGE						
AVERAGE OF ALL SAMPLES TESTED (% removals	91	82	88	99.4		
Range % (# of Tests)	70-93 (30)	74-94 (30)	81-91 (30)	98.7-99.6 (7)		

APPENDIX B

CUMULATIVE PROBABILITY CHARTS



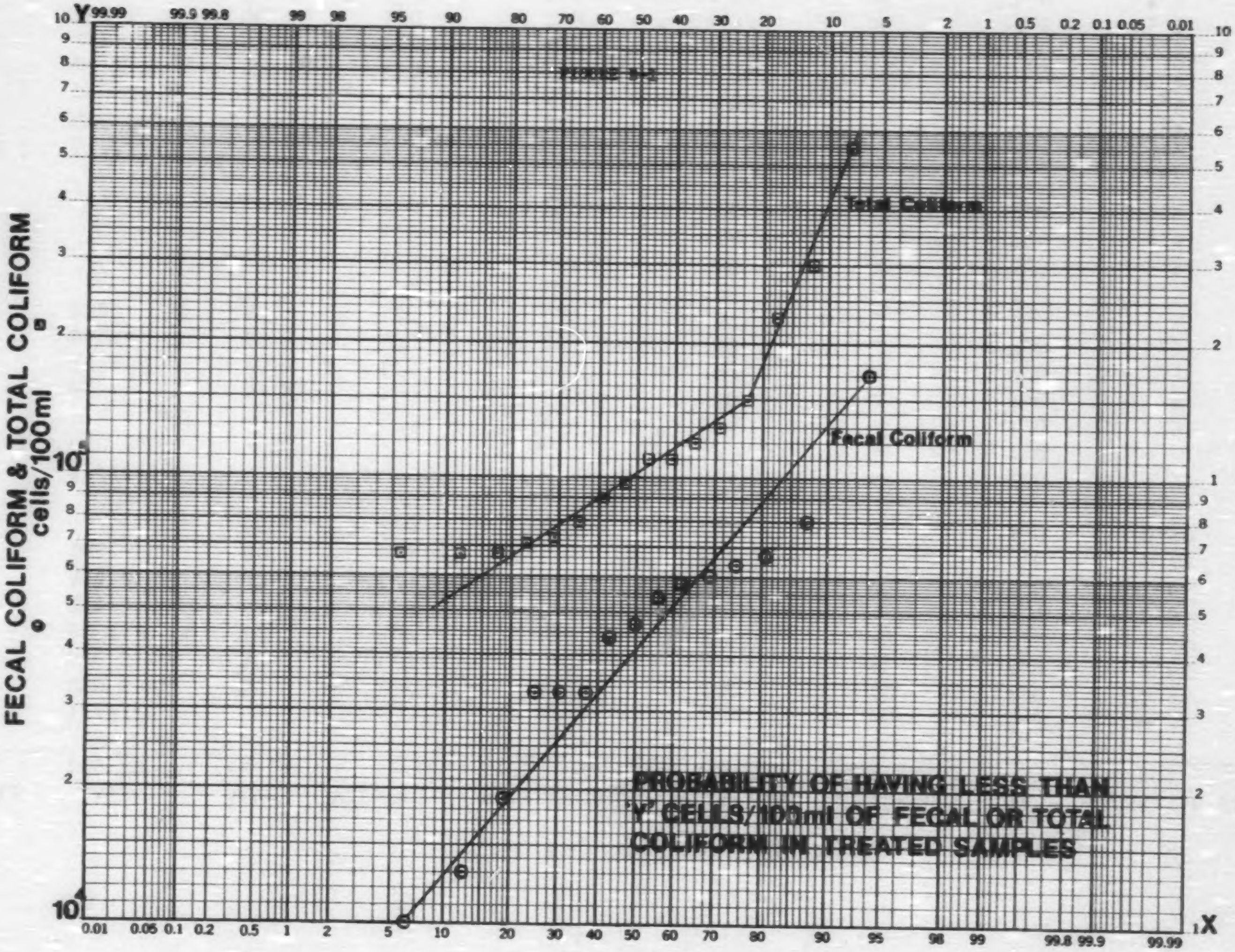


FIGURE 5-2

FECAL COLIFORM & TOTAL COLIFORM
cells/100ml
Y
X
Total Coliform
Fecal Coliform
PROBABILITY OF HAVING LESS THAN 'Y' CELLS/100ml OF FECAL OR TOTAL COLIFORM IN TREATED SAMPLES
10^5
10^4
1
2
3
4
5
6
7
8
9
10
99.99
99.9
99.8
99
98
95
90
80
70
60
50
40
30
20
10
5
2
1
0.5
0.2
0.1
0.05
0.01

APPENDIX C

RAW DATA

BENCH TEST TREATMENT CONDITIONS

SAMPLE NO.	DATE TESTED	ALUM (mg/1)	MAGNETITE (g/1)	POLYELECTRO-LYTE (mg/1)	FLOW RATE (1/min)	RESIDENCE TIME (min)	pH	MAGNETIC FIELD (kG)
Feed 1	12/9/75	-	-	-	-	-	7.0	-
A1	CSO Sam-	60	1.0	1.0	2.2	4	7.0	1.9
A2	ple Size	60	1.0	1.0	2.2	4	7.0	1.65
A3	of 1.6	60	1.0	1.0	2.2	4	7.0	1.65
A4	liters	60	1.0	1.0	2.2	4	7.0	1.3
A5	Bench	60	1.0	1.0	2.2	4	7.0	1.0
A6	Tests	60	1.0	1.0	2.2	4	7.0	0.75
A7		60	1.0	1.0	2.2	4	7.0	0.50
Feed 2	12/11/75	-	-	-	-	-	7.0	-
Feed 3	CSO Sam-	-	-	-	-	-	7.0	-
B1	ple Size	63	1.0	1.0	120	4	7.0	1.5
B2	of 1.6	63	1.0	1.0	20	4	7.0	1.5
B3	liters	63	1.0	1.0	40	4	7.0	1.5
B4	Bench	63	1.0	1.0	60	4	7.0	1.5
B5	Test	63	1.0	1.0	80	4	7.0	1.5
B6		63	1.0	1.0	100	4	7.0	1.5
B7		63	1.0	1.0	60	4	7.0	1.5
B8		63	1.0	1.0	160	4	7.0	1.5
B9		63	1.0	1.0	205	4	7.0	1.5
Feed 4	12/12/75	-	-	-	-	-	7.0	-
C1	CSO Sam-	20	1.0	1.0	2.36	4	7.0	1.5
C2	ple Size	50	1.0	1.0	2.36	4	7.0	1.5
C3	of 1.6	75	1.0	1.0	2.36	4	7.0	1.5
C4	liters	100	1.0	1.0	2.36	4	7.0	1.5
C5	Bench	150	1.0	1.0	2.36	4	7.0	1.5
C6	Test	200	1.0	1.0	2.36	4	7.0	1.5
C7		100	1.0	1.0	2.36	4	7.0	1.5

BENCH TEST PERFORMANCE DATA

SAMPLE NO.	COLOR (PCU)	TURBIDITY (FTU)	SUSPENDED SOLIDS (mg/1)	SETTLEABLE SOLIDS	TOTAL COLIFORM BACTERIA ON EMB AGAR AT $37^\circ C$ (cells/100ml)
Feed 1	185	63	25.7	Small Fibers	-----
A1	19	6	1.5	0	-----
A2	26	5	-	0	-----
A3	27	6	2.4	0	-----
A4	28	5	3.5	0	-----
A5	30	6	0.8	0	-----
A6	28	5	-	0	-----
A7	32	5	0.8	0	-----
Feed 2	190	62	32.3	Small Fibers	1.6×10^8
Feed 3	< 195	< 64	< 30.3	0	-----
B1	22	5	2.2	0	-----
B2	27	5	1.8	0	-----
B3	31	5	1.6	0	-----
B4	21	5	0.9	0	-----
B5	18	5	1.6	0	-----
B6	21	5	3.4	0	3.4×10^6
B7	27	6	1.5	0	-----
B8	29	2	1.3	0	-----
B9	25	5	3.5	0	-----
Feed 4	260	86	46.1	Some Fibers	-----
C1	55	11	6.5	0	-----
C2	30	6	3.4	0	-----
C3	31	5	3.2	0	-----
C4	27	4	2.8	0	-----
C5	26	5	5.6	0	1.4×10^5
C6	36	7	7.9	0	-----
C7	21	4	3.1	0	-----

BENCH TEST TREATMENT CONDITIONS

SAMPLE NO.	DATE TESTED	ALUM (mg/1)	MAGNETITE (g/1)	POLYELECTRO-LYTE (mg/1)	FLOW RATE (1/min)	RESIDENCE TIME (min)	pH	MAGNETIC FIELD (kG)
Feed 5	12/12/75	-	-	-	-	-	7.0	-
D0	CSO Sam-	63	1.0	0	2.3	4	7.0	1.5
D1	ple Size	63	1.0	.25	2.3	4	7.0	1.5
D2	of 1.6	63	1.0	.50	2.3	4	7.0	1.5
D3	liters	63	1.0	.75	2.3	4	7.0	1.5
D4	Bench	63	1.0	1.0	2.3	4	7.0	1.5
D5	Test	63	1.0	1.25	2.3	4	7.0	1.5
D6		63	1.0	1.50	2.3	4	7.0	1.5
D7		63	1.0	1.0	2.3	4	7.0	1.5
Feed 6	12/12/75	-	-	-	-	-	7.0	-
E1	CSO Sam-	63	50	1.0	2.3	4	7.0	1.5
E2	ple Size	63	100	1.0	2.3	4	7.0	1.5
E3	of 1.6	63	250	1.0	2.3	4	7.0	1.5
E4	liters	63	500	1.0	2.3	4	7.0	1.5
E5	Bench	63	1000	1.0	2.3	4	7.0	1.5
E6	Test	63	2500	1.0	2.3	4	7.0	1.5
E7		63	5000	1.0	2.3	4	7.0	1.5
E8		63	500	1.0	2.3	4	7.0	1.5

BENCH TEST PERFORMANCE DATA

SAMPLE NO.	COLOR (PCU)	TURBIDITY (FTU)	SUSPENDED SOLIDS (mg/1)	SETTLEABLE SOLIDS	TOTAL COLIFORM BACTERIA ON EMB AGAR AT 37^{o}C (cells/100ml)
Feed 5	270	88	39.6	Fibers	-----
D0	35	5	2.6	0	1.3×10^{7}
D1	38	5	3.0	0	-----
D2	37	5	2.4	0	-----
D3	40	5	2.9	0	-----
D4	39	6	3.3	0	-----
D5	38	5	3.5	0	-----
D6	37	6	2.2	0	-----
D7	37	5	4.0	0	-----
Feed 6	295	95	47.6	Fibers	-----
E1	27	12	1.7	0	-----
E2	27	5	2.5	0	1.3×10^{7}
E3	30	4	2.6	0	-----
E4	33	5	2.1	0	-----
E5	36	5	3.2	0	-----
E6	46	9	3.5	0	-----
E7	55	10	5.2	0	-----
E8	35	7	3.6	0	-----

BENCH TEST TREATMENT CONDITIONS

SAMPLE NO.	DATE TESTED	ALUM (mg/1)	MAGNETITE (g/1)	POLYELECTRO-LYTE (mg/1)	FLOW RATE (1/min)	RESIDENCE TIME (min)	pH	MAGNETIC FIELD (kG)
Feed 7	12/12/75	-	-	-	-	-	7.0	-
H1	CSO Sam-	63	1.0	1.0	2.3	1	7.0	1.5
H2	ple Size	63	1.0	1.0	2.3	2	7.0	1.5
H3	of 1.6	63	1.0	1.0	2.3	3	7.0	1.5
H4	liters	63	1.0	1.0	2.3	4	7.0	1.5
H5	Bench	63	1.0	1.0	2.3	6	7.0	1.5
H6	Tests	63	1.0	1.0	2.3	10	7.0	1.5
H7		63	1.0	1.0	2.3	3	7.0	1.5
Feed 8	12/12/75	-	-	-	-	-	7.3	-
Feed 9	CSO Sam-	-	-	-	-	-	7.3	-
G1	ple Size	63	1.0	1.0	2.3	4	4.5	1.5
G2	of 1.6	63	1.0	1.0	2.3	4	5.5	1.5
G3	liters	63	1.0	1.0	2.3	4	6.0	1.5
G4	Bench	63	1.0	1.0	2.3	4	6.5	1.5
G5	Test	63	1.0	1.0	2.3	4	7.2	1.5
G6		63	1.0	1.0	2.3	4	7.0	1.5
G7		63	1.0	1.0	2.3	4	7.5	1.5
G8		63	1.0	1.0	2.3	4	6.5	1.5
Feed	12/19/75	-	-	-	-	-	7.0	-
T1	CSO Sam-	50	1.0	1.0	4	3	7.0	1.9
T2	ple Size	50	0.50	1.0	4	3	7.0	1.9
T3	of 10 1.	50	0.25	1.0	4	3	7.0	1.9
Feed 1	12/26/75	-	-	-	-	-	7.2	-
Feed 2	Raw Sew-	-	-	-	-	-	7.2	-
L1	age Sam-	150	.5	2.4	4	3	7.2	1.9
L2	ple Size	150	.75	2.4	4	3	7.2	1.9
L3	of 10 1.	150	.75	2.4	4	3	7.2	1.9

BENCH TEST PERFORMANCE DATA

SAMPLE NO.	COLOR (PCU)	TURBIDITY (FTU)	SUSPENDED SOLIDS (mg/1)	SETTLEABLE SOLIDS	COLIFORM BACTERIA FECAL/TOTAL (cells/100ml)
Feed 7	430	158	62.1	0	---/8 x 10^8
H1	31	5	2.0	0	---/---
H2	30	5	1.7	0	---/---
H3	26	7	2.2	0	---/---
H4	33	4	1.9	0	---/---
H5	24	5	1.7	0	---/---
H6	34	6	2.0	0	---/---
H7	31	6	2.7	0	---/---
Feed 8	55	48	27.6	Fibers	---/---
Feed 9	<448	<165	<55.2	<Fibers	---/---
G1	106	24	12.8	0	---/---
G2	95	19	16.3	0	---/---
G3	58	12	9.6	0	---/---
G4	51	8	4.3	0	---/---
G5	55	8	7.3	0	---/---
G6	43	9	6.4	0	---/---
G7	43	8	6.5	0	---/---
G8	30	5	7.1	0	---/---
Feed	405	145	209	-	---/---
T1	68	17	18.5	-	---/---
T2	52	10	7.8	-	---/---
T3	66	13	23.9	-	---/---
Feed 4	480	48	41.3	-	---/---
Feed 2	-	-	41.9	-	---/---
L1	27	5	4.4	-	---/---
L2	68	18	11.2	-	---/---
L3	-	-	12.6		---/---

BENCH TEST TREATMENT CONDITIONS

SAMPLE NO.	DATE TESTED	ALUM (mg/1)	MAGNETITE (g/1)	POLYELECTROLYTE (mg/1)	FLOW RATE (1/min)	RESIDENCE TIME (min)	pH	MAGNETIC FIELD (kG)
Feed 1	1/1/76 Raw Sewage Sample Size of 10 liters Bench Tests	-	-	-	-	-	7.0	-
A1		100	0.5	1.0	4.0	3.5	7.0	1.9
A2		100	1.0	1.0	4.0	3.5	7.0	1.9
A3		100	0.4	1.0	4.0	3.5	7.0	1.9
A4		100	0.4	1.0	4.0	3.5	7.0	1.9
A5		100	0.5	1.0	4.0	3.5	7.0	1.9
A6		100	0.5	1.0	4.0	3.5	7.0	1.9
A7		100	0.75	1.0	4.0	3.5	7.0	1.9
A8		100	0.75	1.0	4.0	3.5	7.0	1.9
Feed 2	1/1/76 Raw Sewage Sample Size of 10 liters Bench Test	-	-	-	-	-	7.0	-
B1		100	0.5	0.4	4.0	3.5	7.0	1.9
B2		100	0.5	0.8	4.0	3.5	7.0	1.9
B3		100	0.5	1.5	4.0	3.5	7.0	1.9
Feed 3		-	-	-	-	-	7.0	-
C1		100	0.5	1.0	4.0	3.5	7.0	1.0
C2		100	0.4	1.0	4.0	3.5	7.0	1.0
C3-1		100	0.3	1.0	4.0	3.5	7.0	1.0
C3-3		100	0.3	1.0	4.0	3.5	7.0	1.0
C3-2		100	0.3	1.0	4.0	3.5	7.0	1.0
C4		100	0.2	1.0	4.0	3.5	7.0	1.0
C5		100	0.1	1.0	4.0	3.5	7.0	1.0
Feed 4	1/2/76 Raw Sewage Sample Size of 10 liters Bench Tests	-	-	-	-	-	7.0	-
D1		100	0.5	1.0	6.0	3.5	7.0	1.0
D2		100	0.5	1.0	8.0	3.5	7.0	1.0
D3		100	0.5	1.0	10.0	3.5	7.0	1.5

BENCH TEST PERFORMANCE DATA

SAMPLE NO.	COLOR (PCU)	TURBIDITY (FTU)	SUSPENDED SOLIDS (mg/1)	SETTLEABLE SOLIDS (ml/1)	COLIFORM BACTERIA FECAL/TOTAL (cells/100ml)
Feed 1	760	125	191	3.25	---/---
A1	38	9	3.2	-	---/---
A2	42	10	4.5	-	---/---
A3	-	-	10.5	-	---/---
A4	-	-	-	-	---/---
A5	-	-	-	-	---/---
A6	-	-	-	-	---/---
A7	-	-	11.2	-	---/---
A8	-	-	12.6	-	---/---
Feed 2	1000	345-370	295	-	---/---
B1	-	-	-	-	---/---
B2	-	-	11.0	-	---/---
B3	-	-	-	-	---/---
Feed 3	-	-	360	-	---/---
C1	17	3	1.8	-	---/---
C2	29	6	3.5	-	---/---
C3-1	28	6	4.2	-	$7 \times 10^5/2 \times 10^7$
C3-3	32	4	3.7	-	---/---
C3-2	-	-	5.6	-	---/---
C4	-	-	34.4	-	---/---
C5	-	-	12.7	-	---/---
Feed 4	960	430	538	-	$1.5 \times 10^7/5 \times 10^8$
D1	31	6	3.5	-	---/---
D2	43	10	7.0	-	---/---
D3	28	6	5.8	-	---/---

BENCH TEST TREATMENT CONDITIONS

SAMPLE NO.	DATE TESTED	ALUM (mg/l)	MAGNETITE (g/l)	POLYELECTRO-LYTE (mg/l)	FLOW RATE (l/min)	RESIDENCE TIME (min)	pH	MAGNETIC FIELD (kG)
Feed	1/28/76	-	-	-	-	-	7.0	-
1	CSO Sam-	50	1.0	3.0	4.0	5.0	7.0	1.0
2	ple Size	50	0.5	3.0	4.0	5.0	7.0	1.0
3	of 4	50	0.25	3.0	4.0	5.0	7.0	1.0
4	liters	25	0.25	1.0	4.0	5.0	7.0	1.0
5	Bench	50	0.25	1.0	4.0	5.0	7.0	1.0
6	Test	75	0.25	1.0	4.0	5.0	7.0	1.0
7		50	1.0	1.0	4.0	5.0	7.0	1.0
8		50	1.0	2.0	4.0	5.0	7.0	1.0
9		50	1.0	3.0	4.0	5.0	7.0	1.0

BENCH TEST PERFORMANCE DATA

SAMPLE NO.	COLOR (PCU)	TURBIDITY (FTU)	SUSPENDED SOLIDS (mg/1)
Feed	220	68	67
1	78	16	14.8
2	82	16	14.4
3	100	18	8.5
4	96	15	9.8
5	69	8	5.5
6	78	14	10.8
7	62	12	6.1
8	71	12	8.8
9	72	14	7.8

PILOT PLANT TREATMENT CONDITIONS

SAMPLE NO.	DATE TESTED	ALUM (mg/1)	MAGNETITE (g/1)	POLYELECTROLYTE (mg/1)	FLOW RATE (1/min)	RESIDENCE TIME (min)	pH	TIME(min) IN CYCLE SAMPLE TAKEN	MAGNETIC FIELD (kG)
Feed	1/30/76 Raw Sewage Pilot Plant	-	-	-	-	-	7.6	-	-
A1		50	0.5	3	4	3	7.6	0-.5	1.4
A2		50	.5	3	4	3	7.6	1-1.5	1.4
A3		50	.5	3	4	3	7.6	2-2.5	1.4
A4		50	.5	3	4	3	7.6	2.5-3	1.4
B1		50	.5	3	4	3	7.6	0-.5	1.4
B2		50	.5	3	4	3	7.6	1-1.5	1.4
B3		50	.5	3	4	3	7.6	2-2.5	1.4
B4		50	.5	3	4	3	7.6	2.5-3	1.4
C1		50	.5	3	4	3	7.6	0-.5	1.4
C2		50	.5	3	4	3	7.6	1-1.5	1.4
C3		50	.5	3	4	3	7.6	2-2.5	1.4
C4		50	.5	3	4	3	7.6	2.5-3	1.4
D1		50	.5	2	4	3	7.6	1.5	1.4
D2		50	.5	2	4	3	7.6	1.5	1.4
E1		50	.5	1	4	3	7.6	1.5	1.4
E2		50	.5	1	4	3	7.6	1.5	1.4
G1		50	.5	3	4	3	7.6	2-2.5	1.4
G2		50	.5	3	4	3	7.6	4-4.5	1.4
G3		50	.5	3	4	3	7.6	6-6.6	1.4
G4		50	.5	3	4	3	7.6	8-8.5	1.4
G5		50	.5	3	4	3	7.6	10-10.5	1.4
G6		50	.5	3	4	3	7.6	11-11.5	1.4

PILOT PLANT PERFORMANCE DATA

SAMPLE NO.	COLOR (PCU)	TURBIDITY (FTU)	SUSPENDED SOLIDS (mg/1)
Feed	325	112	114
A1	53	10	10.1
A2	59	12	11.0
A3	60	11	9.8
A4	63	13	9.0
B1	51	10	8.0
B2	60	11	9.2
B3	57	11	7.8
B4	58	11	8.3
C1	61	10	10.7
C2	61	13	8.8
C3	70	14	10.8
C4	79	17	11.5
D1			
D2	63	13	9.4
E1	69	12	10.1
E2	69	12	11.0
G1	84	21	11.1
G2	83	20	10.8
G3	62	11	9.7
G4	62	12	9.6
G5	71	16	10.1
G6	61	18	8.0

PILOT PLANT TREATMENT CONDITIONS

SAMPLE NO.	DATE TESTED	ALUM (mg/1)	MAGNETITE (g/1)	POLYELECTRO-LYTE (mg/1)	FLOW RATE (1/min)	RESIDENCE TIME (min)	pH	TIME(min) IN CYCLE SAMPLE TAKEN	MAGNETIC FIELD (kG)
Feed	2/3/76	-	-	-	-	-	7.0	-	-
MA1	CSO	50	.5	1	4	3	7.0	3-4	1.4
MB1	Pilot	50	.5	1	4	3	7.0	3-4	1.4
MA2	Plant	50	.35	1	4	3	7.0	3-4	1.4
MB2	Cycle	50	.35	1	4	3	7.0	3-4	1.4
MC2	Time	50	.35	1	4	3	7.0	3-4	1.4
MA3	4 min.	50	.2	1	4	3	7.0	3-4	1.4
MB3		50	.2	1	4	3	7.0	3-4	1.4
MA4		50	.1	1	4	3	7.0	3-4	1.4
MB4		50	.1	1	4	3	7.0	3-4	1.4
MA5		50	.05	1	4	3	7.0	3-4	1.4
MB5		50	.05	1	4	3	7.0	3-4	1.4
MA6		50	.8	1	4	3	7.0	3-4	1.4
Feed 2		50	-	-	-	-	7.0	-	-

PILOT PLANT PERFORMANCE DATA

SAMPLE NO.	COLOR (PCU)	TURBIDITY (FTU)	SUSPENDED SOLIDS (mg/1)	COLIFORM BACTERIA FECAL/TOTAL (100 cells/ml)
Feed	255	88	112	$2.0 \times 10^6/2.3 \times 10^7$
MA1	26	5	4.1	------------------
MB1	27	4	4.5	
MA2	29	5	3.6	$1.0 \times 10^5/2.7 \times 10^6$
MB2	30	6	5.4	------------------
MC2	28	6	4.5	------------------
MA3	29	6	3.9	------------------
MB3	38	7	7.7	------------------
MA4	45	7	8.7	------------------
MB4	38	6	7.6	------------------
MA5	125	25	30.6	------------------
MB5	98	20	25.5	------------------
MA6	37	5	5.3	------------------
Feed 2	385-415	150	261	------------------

BENCH TEST TREATMENT CONDITIONS

SAMPLE NO.	DATE TESTED	ALUM (mg/1)	MAGNETITE (g/1)	POLYELECTRO-LYTE (mg/1)	FLOW RATE (1/min)	RESIDENCE TIME (min)	pH	TIME(min) IN CYCLE SAMPLE TAKEN	MAGNETIC FIELD (kG)
Ala	3/2/76	50	.2	1	4	3	7.07	-	1.9
Alb	Raw Sew-	50	.2	1	4	3	7.07	-	1.9
Alc	age Sam-	50	.2	1	4	3	7.10	-	1.9
A2A	ple Size	50	.8	3	4	3	7.07	-	1.9
A2B	4 liters	50	.8	3	4	3	7.15	-	1.9
A3A	Bench	50	.8	3	4	3	6.06	-	1.9
A3B	Test	50	.8	3	4	3	6.04	-	1.9
A4A		50	.8	3	4	3	7.55	-	1.9
A4B		50	.8	3	4	3	7.49	-	1.9
A5A		50	.8	3	4	3	8.30	-	1.9
A5B		50	.8	3	4	3	8.21	-	1.9
Feed		-	-	-	-	-	7.07	-	-
Feed		-	-	-	-	-	7.07	-	-
X1	3/8/76	0	.5	4	1	10	8.00	-	1.95
X2	Raw Sew-	100	.5	0	1	10	6.49	-	1.95
X3	age Sam-	100	.5	1.8	1	10	7.10	-	1.95
X4	ple Size	100	.5	0	1	10	5.49	-	1.95
X5	4 liters	100	.5	0	1	10	6.00	-	1.95
X6	Bench	100	.5	5	1	10	7.99	-	1.95
X7	Test	100	.5	1.8	1	10	7.09	-	1.95
X8		100	.5	5	1	10	7.14	-	1.95
Feed		-	-	-	-	-	7.09	-	-

BENCH TEST PERFORMANCE DATA

SAMPLE NO.	COLOR (PCU)	TURBIDITY (FTU)	SUSPENDED SOLIDS (mg/l)	COLIFORM BACTERIA FECAL (100 cells/ml)
A1a	---	---	12.3	--------
A1b	---	---	9.0	--------
A1c	---	---	203.7	--------
A2A	---	---	8.9	--------
A2B	---	---	10.4	--------
A3A	---	---	12.6	--------
A3B	---	---	11.9	--------
A4A	---	---	7.8	--------
A4B	---	---	9.8	--------
A5A	---	---	11.9	--------
A5B	---	---	10.9	--------
Feed	---	---	73.3	--------
Feed	---	---	110.8	--------
X1	135	25	17.4	6.0×10^6
X2	46	6	4.9	7.0×10^4
X3	49	7	5.4	7.1×10^4
X4	71	12	-	5.6×10^4
X5	62	9	15.6	1.0×10^5
X6	50	8	9.2	1.8×10^5
X7	41	6	7.2	6.5×10^4
X8	49	7	7.9	8.4×10^4
Feed	320	105	147	1.4×10^7

PILOT PLANT TREATMENT CONDITIONS

SAMPLE NO.	DATE TESTED	ALUM (mg/1)	MAGNETITE (g/1)	POLYELECTRO-LYTE (mg/1)	FLOW RATE (1/min)	RESIDENCE TIME (min)	pH	TIME(min) IN CYCLE SAMPLE TAKEN	MAGNETIC FIELD (kG)
P1A	3/17/76	100	.2	2.5	4	3	7.34	3-3.5	1.6
P1A2	CSO, CYCLE	100	.2	2.5	4	3	7.34	3-3.5	1.6
P1B	TIME 4 Min.	100	.2	2.0	4	3	7.34	3-3.5	1.6
P2A	Pilot	100	.2	1.0	4	3	7.34	3-3.5	1.6
P2A2	Plant	100	.2	1.0	4	3	7.34	3-3.5	1.6
P2B		100	.2	1.0	4	3	7.34	3-3.5	1.6
P3A		100	.2	.5	4	3	7.34	3-3.5	1.6
P4A		100	.2	.1	4	3	7.34	3-3.5	1.6
P5A		100	.2	0	4	3	7.34	3-3.5	1.6
A1A		200	.5	2.5	4	3	7.34	3-3.5	1.6
A2A		150	.5	2.5	4	3	7.34	3-3.5	1.6
A3A		100	.5	2.5	4	3	7.34	3-3.5	1.6
A3B		100	.5	2.5	4	3	7.34	3-3.5	1.6
A3C		100	.5	2.5	4	3	7.34	3-3.5	1.6
A4A		70	.5	2.5	4	3	7.34	3-3.5	1.6
A5A		50	.5	2.5	4	3	7.34	1-1.5	1.6
ML1A	CYCLE	100	.5	1.0	4	3	7.34	4-4.5	1.6
ML2A	TIME	100	.5	1.0	4	3	7.34	8-8.5	1.6
ML3A	20 min.	100	.5	1.0	4	3	7.34	12-12.5	1.6
ML4A		100	.5	1.0	4	3	7.34	16-16.5	1.6
ML5A		100	.5	1.0	4	3	7.34	20-20.5	1.6
ML6A		100	.5	1.0	4	3	7.34	1-1.5	1.6
ML1B		100	.5	1.0	4	3	7.34	4-4.5	1.6
ML2B		100	.5	1.0	4	3	7.34	8-8.5	1.6
ML3B		100	.5	1.0	4	3	7.34	12-12.5	1.6
ML4B		100	.5	1.0	4	3	7.34	16-16.5	1.6
ML5B		100	.5	1.0	4	3	7.34	20-20.5	1.6
ML6B		100	.5	1.0					

PILOT PLANT PERFORMANCE DATA

SAMPLE NO.	COLOR (PCU)	TURBIDITY (FTU)	SUSPENDED SOLIDS (mg/1)
P1A	83	14	15.3
P1A2	67	11	10.2
P1B	79	15	15.1
P2A	81	16	23.0
P2A2	72	10	11.7
P2B	100	16	26.0
P3A	84	13	33.0
P4A	160	49	66.0
P5A	210	57	94.0
A1A	110	33	49.0
A2A	83	14	17.6
A3A	73	11	12.3
A3B	71	10	9.0
A3C	64	11	9.7
A4A	119	25	24.0
A5A	120	41	52.0
ML1A	63	10	14.5
ML2A	75	15	12.7
ML3A	94	17	30.0
ML4A	134	29	38.0
ML5A	110	49	72.0
ML6A	170	65	185.0
ML1B	78	8	13.8
ML2B	87	14	22
ML3B	95	18	33
ML4B	90	29	38
ML5B	130	30	57
ML6B	170	53	99

PILOT PLANT TREATMENT CONDITIONS

SAMPLE No.	DATE TESTED	ALUM (mg/1)	MAGNETITE (g/1)	POLYELECTRO-LYTE (mg/1)	FLOW RATE (1/min)	RESIDENCE TIME (min)	pH	TIME(min) IN CYCLE SAMPLE TAKEN	MAGNETIC FIELD (kG)
RC1	3/17/76	100	.42	2.4	1	12	7.34	2.5-4.5	1.6
RC2	CSO	100	.42	2.4	1	12	7.34	1-4.5	1.6
RC3	CYCLE TIME	100	.42	2.4	1	12	7.34	1-4	1.6
RC4	4 min.	100	.42	2.4	1	12	7.34	1-4	1.6
RC5		100	.42	2.4	1	12	7.34	2-4	1.6
RC6		100	.42	2.4	1	12	7.34	2.5-4	1.6
RC7		100	.42	2.4	1	12	7.34	1-4	1.6
RC8		100	.42	2.4	1	12	7.34	1-4	1.6
RC9		100	.42	2.4	1	12	7.34	1-4	1.6
RC10		100	.42	2.4	1	12	7.34	1-4	1.6
SS1		100	.5	2.5	1	12	7.34	1-4	0.5
SS2A		100	.5	2.5	4	3	7.34	2-4	1.0
SS2B		100	.5	2.5	4	3	7.34	2-4	0.5
SS2C		100	.5	2.5	4	3	7.34	2-4	1.9
Feed1	-	-	-	-	-	-	7.34	-	-
Feed 2		-	-	-	-	-	7.34	-	-

PILOT PLANT PERFORMANCE DATA

SAMPLE NO.	COLOR (PCU)	TURBIDITY (FTU)	SUSPENDED SOLIDS (mg/1)	COLIFORM BACTERIA FECAL (100 cells/ml)	COLIFORM BACTERIA TOTAL	BOD $_5$
RC1	50	8	8.1	---------	---------	--
RC2	50	8	7.4	2.3×10^4	7.0×10^4	5.2
RC3	53	11	7.0	--------	--------	--
RC4	50	8	9.1	4.6×10^4	8.1×10^4	5.7
RC5	51	9	5.5	4.3×10^4	7.6×10^4	--
RC6	44	8	4.4	1.7×10^4	1.1×10^5	--
RC7	42	8	10.6	--------	--------	--
RC8	45	8	4.5	6.4×10^4	1.2×10^5	5.9
RC9	42	8	4.3	---------	---------	--
RC10	41	8	4.1	1.3×10^5	2.7×10^5	7.0
SS1	46	8	4.5	---------	1.3×10^5	--
SS2A	61	11	9.8	---------	---------	--
SS2B	64	10	13.0	---------	---------	--
SS2C	61	9	8.5	--------	--------	--
Feed 1	650	230	460	2.6×10^7	5.9×10^7	75
Feed 2	800	250	520	4.6×10^7	6.6×10^7	83

APPENDIX D

GLOSSARY

Backflush - A rapid reverse flow of water through the separator matrix with the magnet deenergized following a filtering interval which serves to purge accumulated magnetic flocs from the matrix.

Bench Test - A test performed manually on an aliquot of sample. More specifically, a waste water sample is treated with known concentrations of flocculants and seed while agitating, and is then passed through a gravity feed high gradient magnetic separator and later analyzed.

Canister - The cylindrical copper or stainless steel container holding the magnetic matrix.

Combined Sewer Overflow or Combined Storm Overflow (CSO) - A flow from a sewer receiving both surface run off and municipal sewage in excess of interceptor capacity that is discharged into a receiving water.

Continuous Pilot Plant - Small scale sewage treatment plant which is set to cycle automatically and continuously for feasibility studies.

Dry Weather Flow - The flow of municipal sewage during a dry spell in a sewer also able to receive runoff.

First Flush - The condition, often occurring in storm sewer discharges and combined sewer overflows, in which a disproportionately high pollutional load is carried in the first portion of the discharge or overflow.

Flocculation Chain (or train) - A series of interconnected mixing tanks in which flocculants and magnetic seed are added to the water to be treated by magnetic separation.

High Gradient Magnetic Separator - A solenoid electromagnet containing a filamentary ferromagnetic matrix and encased in a highly efficient iron return frame.

Jar Test - Standard sewage treatment test in which several aliquots of waste water are taken and treated with various concentrations of flocculants, etc., to determine optimal dosages necessary for effective treatment.

Magnetic Matrix - The ferromagnetic material (steel wool or expanded metal) located in the canister of a high gradient magnetic separator.

Matrix Loading - The ratio of the weight of solids successfully held in the magnetic matrix to the weight of matrix fiber.

Pilot Plant Cycle - Series of automatically timed and executed continuous cycles including: reset, magnet on delay, filter, magnet off delay, flush and dump cycles.

Sludge - Semi-solid end product of magnetic separation process consisting of waste solids, magnetic seed and flocculants.

Surge Flow - Rapid increase in incoming volume of waste water into a treatment or detention facility.

Wet Weather Flow - A waste water containing both runoff and raw sewage resulting from the combining of storm waters with normal dry weather flow.

APPENDIX E

ABBREVIATIONS AND MAGNETIC UNITS

Abbreviation	Description
BOD_5	Five-day Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CSO	Combined Storm Overflow
EMB	Eosin Methylene Blue Agar Medium
FTU	Formazin Turbidity Units (= Jackson Turbidity Units)
PCU	Platinum-Cobalt Unit for Color (1 Color Unit = 1 mg/l Platinum as Chloroplatinate Ion)
PFU	Plaque Forming Unit (For Virus Analysis, One PFU represents one Virus in Original Sample)

Magnetic Unit	Description
g/g	A term used in matrix loading discussions meaning number of grams of solids held by the matrix (magnetically) per gram of matrix fiber.
kG	Unit of magnetic field strength (Kilogauss) (1 kG = 6452 lines/square inch)
m/hr	Flow velocity through a unit area of a magnetic matrix (number of cubic meters of water passing through a square meter of matrix surface area in one hour). (1 m/hr = 0.41 gallons/min ft^2, and for our 1.5 inch diameter matrices this is equivalent to a flow flux rate of 0.018 liters/min).

APPENDIX F

CONVERSION FACTORS

CONVERSION FACTORS*
English to Metric

English unit	Abbr.	Multiplier	Abbr.	Metric unit
acre	acre	0.405	ha	hectare
acre-foot	acre-ft	1,233.5	cu m	cubic meter
cubic foot	cf	28.32	l	liter
cubic feet per minute	cfm	0.0283	cu m/min	cubic meters per minute
cubic feet per second	cfs	28.32	l/sec	liters per second
cubic inch	cu in.	16.39 0.0164	cu cm l	cubic centimeter liter
cubic yard	cy	0.765 764.6	cu m l	cubic meter liter
degree Fahrenheit	deg F	0.555 (°F-32)	deg C	degree Celsius
feet per minute	fpm	0.00508	m/sec	meters per second
feet per second	fps	0.305	m/sec	meters per second
foot (feet)	ft	0.305	m	meter(s)
gallon(s)	gal.	3.785	l	liter(s)
gallons per acre per day	gad	9.353	l/day/ha	liters per day per hectare
gallons per capita per day	gcd	3.785	l/capita/day	liters per capita per day
gallons per day	gpd	4.381 x 10^{-5}	l/sec	liters per second
gallons per day per square foot	gpd/sq ft	1.698 x 10^{-3} 0.283	cu m/hr/sq m cu m/min/ha	cubic meters per hour per square meter cubic meters per minute per hectare
gallons per minute	gpm	0.0631	l/sec	liters per second
gallons per minute per square foot	gpm/sq ft	2.445 0.679	cu/m/hr/sq m l/sec/sq m	cubic meters per hour per square meter liters per second per square meter
gallons per square foot	gpsf	40.743	l/sq m	liters per square meter
horsepower	hp	0.746	kw	kilowatts
inch(es)	in.	2.54	cm	centimeter
inches per hour	in./hr	2.54	cm/hr	centimeters per hour
million gallons	mil gal.	3.785 3,785.0	Ml cu m	megaliters (liters x 10^6) cubic meters
million gallons per acre per day	mgad	0.039	cu m/hr/sq m	cubic meters per hour per square meter
million gallons per day	mgd	43.808 0.0438	l/sec cu m/sec	liters per second cubic meters per second
mile	mi	1.609	km	kilometer
parts per billion	ppb	0.001	mg/l	milligrams per liter
parts per million	ppm	1.0	mg/l	milligrams per liter
pound(s)	lb	0.454 453.6	kg g	kilogram grams
pounds per acre per day	lb/acre/day	0.112	g/day/sq m	grams per day per square meter
pounds per day per acre	lb/day/acre	1.121	kg/day/ha	kilograms per day per hectare
pounds per 1,000 cubic feet	lb/1,000 cf	16.077	g/cu m	grams per cubic meter
pounds per million gallons	lb/mil gal.	0.120	mg/l	milligrams per liter
pounds per cubic foot	pcf	16.02	kg/cu m	kilograms per cubic meter
pounds per square foot	psf	4.882 x 10^{-4}	kg/sq cm	kilograms per square centimeter
pounds per square inch	psi	0.0703	kg/sq cm	kilograms per square centimeter
square foot	sq ft	0.0929	sq m	square meter
square inch	sq in.	6.452	sq cm	square centimeter
square mile	sq mi	2.590	sq km	square kilometer
square yard	sq yd	0.836	sq m	square meter
standard cubic feet per minute	scfm	1.699	cu m/hr	cubic meters per hour
ton (short)	ton	907.2 0.907	kg metric ton	kilograms metric ton
yard	yd	0.914	m	meter

* Taken from "Urban Stormwater Management and Technology; An Assessment", Metcalf & Eddy, Inc., EPA Contract No. 68-03-0179, December, 1974.